DETERMINATION OF OPTIMUM VALUES FOR VOLTAGE SETPOINTS OF POWER STATIONS IN TURKEY

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ABSTRACT

DETERMINATION OF OPTIMUM VALUES FOR VOLTAGE SETPOINTS OF POWER STATIONS IN TURKEY

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Voltage control is performed in three hierarchical levels in Turkish power system: primary, secondary and tertiary voltage control. Primary and secondary voltage controls are defined as the regulation of the voltage at the generator terminal and at the high voltage busbar of the power plant according to the pre-determined setpoints. The determination of the voltage setpoints for the power plants, which is defined as the tertiary voltage control, is performed by the operators in National and Regional Load Dispatch Centers. This process is based on the operators' experience and knowledge about the system operating conditions and network connections. Since no systematical or analytical approach is employed during this process, optimum voltage profile along the grid may not be reached or transmission losses may increase.

In this thesis study, a systematical approach is developed to guide the system operators during the determination of voltage setpoints for the power plants. For this purpose, an algorithm with two stages is developed. Stage I of the algorithm optimizes the voltage profile along the grid by minimizing the transmission losses. On the other hand, Stage II of the algorithm minimizes the cost of corrective actions if and when they are required.

The algorithm has been developed and simulated using DigSilent and Matlab softwares. As the test system, West Anatolia Region of Turkish network has been chosen. Simulation results reveal that the optimum voltage profile can be obtained and the transmission losses can be minimized by the help of these studies.

Keywords: Optimal Power Flow, Voltage Control, Optimum Voltage Set Points

ÖZ

TÜRKİYEDEKİ ELEKTRİK SANTRALLERİNİN GERİLİM AYAR NOKTALARI İÇİN OPTİMUM DEĞERLERİN BELİRLENMESİ

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Türkiye elektrik sisteminde gerilim kontrolü primer, sekonder ve tersiyer gerilim kontrolü olmak üzere üç seviyede gerçekleştirilmektedir. Primer ve sekonder gerilim kontrolü, santrallerde jeneratör terminali ve yüksek gerilim barasının geriliminin daha önce belirlenmiş ayar noktalarına göre regüle edilmesi olarak tanımlanmıştır. Tersiyer gerilim kontrolü olarak tanımlanan, santraller için ayar noktalarının belirlenmesi de TEİAŞ Milli ve Bölgesel Yük Tevzi Merkezleri'ndeki operatörler tarafından gerçekleştirilmektedir. Bu süreç operatörlerin sistem işletme koşulları ve şebeke bağlantıları ile ilgili bilgi ve deneyimlerine dayanmaktadır. Bu süreçte herhangi bir sistematik veya analitik çalışma gerçekleştirilmemesi sebebiyle şebekede optimum gerilim profiline ulaşılamayabilir. Ayrıca iletim kayıpları artabilir.

Bu tez çalışmasında, sistem operatörlerine santraller için gerilim ayar noktalarının belirlenmesi sürecinde rehberlik etmesi amacıyla sistematik bir yaklaşım geliştirilmiştir. Bu amaçla, iki kısımdan oluşan bir algoritma geliştirilmiştir. Algoritmada Kısım 1 iletim kayıplarını en aza indirerek gerilim profilinin optimum hale gelmesini sağlamaktadır. Diğer yandan, Kısım 2 ise gerekli olduğu durumlarda düzeltici faaliyetlerin maliyetini en aza indirmektedir.

Algoritma DigSilent ve Matlab yazılımları kullanılarak geliştirilmiş ve simüle edilmiştir. Test sistemi olarak Türkiye şebekesinin Batı Anadol Bölgesi seçilmiştir. Bu çalışmalar sonucunda optimum gerilim profiline ulaşıldığı simülasyon sonuçları tarafından açığa çıkarılmıştır. Ayrıca, santrallerin yüksek gerilim baraları için gerilim ayar noktalarının belirlenmesi sürecinde iletim kayıpları en aza indirilmiştir.

Anahtar Kelimeler: Optimum Güç Akışı, Gerilim Kontrolü, Optimum Gerilim Referans Değerleri

To My Family

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CHAPTER 1

INTRODUCTION

The modern power system operation is based on the achievement of four objectives. These are the quality of service, the impact on the environment, the continuity of service and the economy. The most important of all for this thesis study is the quality of service. The quality of service indicates that the energy should be supplied with acceptable voltage and frequency. The services for maintaining an acceptable voltage and frequency are defined as ancillary services, and these services are basically categorized as frequency and voltage control.

Frequency control is related with the power balance which is the condition that the total generated power and the total demand is equal to each other. Since electrical energy can not be stored in large amounts, the generated electrical energy must be consumed at the same time. In case of a power imbalance, frequency will change and actions should be taken to maintain the power balance via frequency control. Similarly, voltage control is related with the reactive power flows along the grid. In order to maintain acceptable voltages, reactive power flows should be controlled.

The key elements of the power systems such as transmission lines, transformers, synchronous and asynchronous machines have capacitive and inductive effects. Due to these effects; reactive power is required for the operation of these network elements. On the other hand; reactive power flows increase the transmission losses. Hence; reactive power flows should not exceed the required amount for the operation of network elements in order to keep the transmission losses minimum.

There are two different approaches about voltage control applications accomplished around the world. Voltage control is performed in three hierarchical levels in each approach: primary, secondary and tertiary voltage control. The difference between these two approaches is the secondary voltage control mechanism. In the first approach, which is performed in some countries such as France and Italy, secondary voltage control is the automatic control of the voltage setpoint values of the generators by the automatic regional controllers. In this approach, the overall grid is split into regions and secondary voltage control is performed locally. For each region, a pilot node is selected and the voltage of this pilot node is regulated at a predetermined value.

In the second approach, which is performed in Turkish power system, secondary voltage control is the regulation of the voltage of the HV (high voltage) busbar of the power plant according to the predetermined voltage setpoint values. The power plants regulate the voltages of the HV busbars by controlling the voltage setpoint value of AVRs (Automatic Voltage Regulators). Automatic Voltage Regulators regulate the terminal voltages of the generators according to the setpoint values. In addition, tertiary voltage control is the determination of the voltage setpoint values for the secondary voltage control.

Tertiary voltage control is performed by the operators in Load Dispatch Centers after the determination of active power dispatch data in the day ahead market. The operators determine the voltage setpoint values for the HV busbars of the power plants based on their knowledge and experience about the power plant considered and the system conditions around the power plant considered. During this process, the operators do not conduct any systematic study. Hence, the reactive power flows along the grid is not considered in detail. This may yield to an increase in reactive power flows along the grid and an increase in transmission losses. In addition to the increase in transmission losses, due to the lack of systematic study for the tertiary voltage control, the voltages along the grid may arise within a wider voltage band.

In this thesis study, a systematic approach is suggested to avoid these possibilities. For this purpose, an algorithm is developed for the determination of setpoint values for high voltage busbars of the power plants. The algorithm determines the optimum voltage setpoint values while satisfying the generator reactive power limits and voltage limits of busbars. The algorithm consists of two stages; voltage profile optimization and minimization of the cost of corrective actions. The voltage profile optimization is developed using DigSilent while the minimization of the cost of corrective actions is developed using Matlab.

In Chapter 2, general background about the ancillary services and the ancillary service mechanisms in Turkey are explained. Principles of frequency control and voltage control are also explained. Different approaches about voltage control are presented. Various voltage control schemes for the regulation of the voltages of high voltage busbars are described. Towards the end of Chapter 2, the voltage control issue in Turkish power system and the suggested approach about this issue is investigated.

Modeling of the system elements for simulation studies are explained in Chapter 3. The system model of Turkish grid is constituted in DigSilent and the network is reduced to West Anatolia Region. The reduction of the network and the tools in the software are detailed in this chapter. Lastly, the overall algorithm is explained in detail in Chapter 3.

In Chapter 4, the details of the stages of the algorithm which are voltage profile optimization and the minimization of the cost of corrective actions, are explained. Stage I is forming the main body of the overall algorithm. The voltage setpoint values for high voltage busbars of the power plants are determined in this stage. Stage I is based on OPF calculations and developed using DigSilent. In this stage, the algorithm aims to find a feasible optimum solution for the voltages along the grid. In case that Stage I can not find a feasible solution for the voltages along the grid, in other words, voltage limits can not be satisfied, Stage II is executed to update the active power dispatch data to get extra reactive power from the power plants. To satisfy the voltage limits of the busbars, extra reactive power is required. This extra reactive power is obtained by decreasing the active power output of the power plants which are in service or taking the power plants into service which are out of service. Stage II minimizes the cost of redispatch of the power plants and developed using Matlab.

In Chapter 5, simulation results are given and these results are discussed. Two scenarios are constituted for simulation studies. In each scenario, the algorithm is executed for 24 times each for an hour. In Scenario 1, the actual topology of the system is used. The system data of the hour, when the peak demand in 2011 occurred, are obtained from TEİAŞ. Simulation results show that voltage limit violations occur in one electrical region in the first scenario. Hence, a second scenario is constituted to observe the results of the algorithm when the voltage limit violations are occurred in two electrical regions. For this purpose, in Scenario 2, a 40 MVAr shunt reactor is connected to the Kocadağ 154 kV busbar to create another voltage limit violation.

In Appendix - A, general information about Optimal Power Flow is presented since optimal power flow performs the main function of the voltage profile optimization problem. Load data used for the modeling of the loads are given in Appendix – B. The active power dispatch data obtained from TEİAŞ are given in Appendix – C; however, the names of the power plants are not given due to the confidentiality issues. In Appendix – D, the voltage setpoints for the high voltage busbars of the power plants that are determined at the end of the simulations are given.

CHAPTER 2

GENERAL BACKGROUND ON ANCILLARY SERVICES AND REACTIVE POWER SUPPORT SERVICE IN TURKEY

2.1. Ancillary Services in Power Systems

There are four main objectives of a modern power system; quality of service, environment, continuity of service and economy. Firstly, the quality of service is the supply of the energy to the user with acceptable voltage and frequency. Secondly, the circumstances that the energy is produced should not have detrimental effects on the environment. The continuity of service is held by ensuring the security and reliability. Security is to maintain the system operating in case of a contingency and reliability is that the system has sufficient reserves for a change in power demand. Lastly, the fourth objective suggests that a modern power system should be planned and operated with the minimum cost to the user.

In order to provide energy with acceptable voltage and frequency to the user, a group of tasks, categorized under ancillary services, can be divided into two main categories: frequency control and voltage control [1]. Frequency control is the control of generated active power in order to maintain the system frequency at an acceptable level, where the voltage control is the control of reactive power generation in order to maintain the voltage magnitudes in the system at acceptable levels.

When the total generated power is larger than the total consumed power plus losses, the power surplus is converted to mechanical energy and stored in rotating masses; hence, the system frequency will increase. If no preventive measures are taken against the increase in system frequency, all rotating machines will speed up. In this case, overspeed protection devices will be activated and generators will be out of service and hence a system blackout may occur.

On the other hand, when generated power is smaller than the total consumed power plus losses, the deficient energy is supplied from the mechanical energy of rotating masses; hence the system frequency will decrease. When the system frequency decreases below a pre-set value, protection devices will be activated and generators will be out of service. Again in this case, system blackout may occur. To avoid this phenomena, system frequency must be controlled and regulated.

All elements in the power system have inductive and capacitive effects in addition to resistive effects. Transmission lines have inductances due to the internal magnetic flux and magnetic flux between conductors; in addition, they have capacitances due to the electric field between the conductors and ground. Likewise, transformers have inductances since the working principles of the transformers are based on electromagnetic fields. Additionally, generators and motors have inductances like the transformers. In other words, the key elements of power systems require reactive power in order to operate properly [2].

However, it must be paid attention to the reactive power flows in the system. Reactive power increases the loading of transmission lines. Besides, when reactive power is insufficient at a region, voltages will be lower than the nominal value. In order to increase the voltage, reactive power must be injected to the system at that region. Therefore, reactive power flows should be neither more nor less than the required amount for proper operation of the network elements. Hence, reactive power flows must be optimized such that the voltage limits of busbars are satisfied, and that is the reactive power control or voltage control.

2.1.1. Frequency Control or Active Power Control

Frequency control is divided into four parts with regards to the realization times: primary, secondary and tertiary frequency control and time control according to ENTSO-E regulations [1]. Primary frequency control is the quickest control, and it is activated in seconds. The reason of being the quickest control action is that it is performed locally by automatic controllers in each generation unit.

Each generation unit must be equipped with a local controller (governor) that controls the active power output of the unit. Governors send signals to the turbine controllers to increase or decrease the output power according to the system frequency. When the system frequency is decreased, it means that a power deficit has been occurred in the system. Thus, the governor will increase the output power of the generator. In the same manner, when the system frequency is increased, a power surplus has been occurred in the system. For that reason, the governor will decrease the output power of the generator. In other words, the governor takes action to stop the increase or decrease in the system frequency.

The governor actions ensure that the balance between the total generated power and the total consumed power is maintained and the system frequency is stabilized. As a result of the governor actions, the system frequency will be stabilized different than the nominal frequency value, 50 Hz in European grid. The system frequency can not be restored to its nominal value by primary frequency control actions; the restoration of the system frequency to its nominal value is performed by secondary frequency control actions.

Secondary frequency control is a central control loop whose activation time is in minutes. It is slower than the primary frequency control and faster than the tertiary frequency control. When a power deficit or power surplus occurs in the system, firstly governors will take action to stabilize the system frequency. Then the secondary frequency control actions take place to restore the system frequency to its nominal value. In this way, the primary frequency reserve, which is activated, will be released and will be ready for another power imbalance.

For secondary frequency control, a central controller is usually established in National Control Centers. This controller controls the active power setpoints of the generators to keep the area control error minimum. The area control error consists of frequency deviation and power exchange with the other control areas. Upon the magnitude of the power imbalance and amount of primary and secondary frequency reserves, secondary frequency control actions may not be sufficient to bring the system frequency up to its nominal value. Or, the system frequency may be brought up to its nominal value but secondary frequency control reserve may not be sufficient for additional disturbances. In this case, tertiary frequency control will take action.

Tertiary frequency control is much slower than the primary and secondary frequency controls. It is performed by the operators at National Control Centers, and it is activated in order to release the primary and the secondary frequency control reserves. There are different ways to implement tertiary frequency control. It can be implemented as an automatic control or manual control.

Finally, time control is the control of frequency setpoint of the interconnected system in order to minimize the difference between the global time and the frequency time. Time control is the last phase of frequency control. When the system frequency is above the nominal value; frequency clock will operate faster than the global time and vice versa. Therefore, every month or year, frequency setpoint is changed from the nominal value in order to decrease the difference between the global time and the system time.

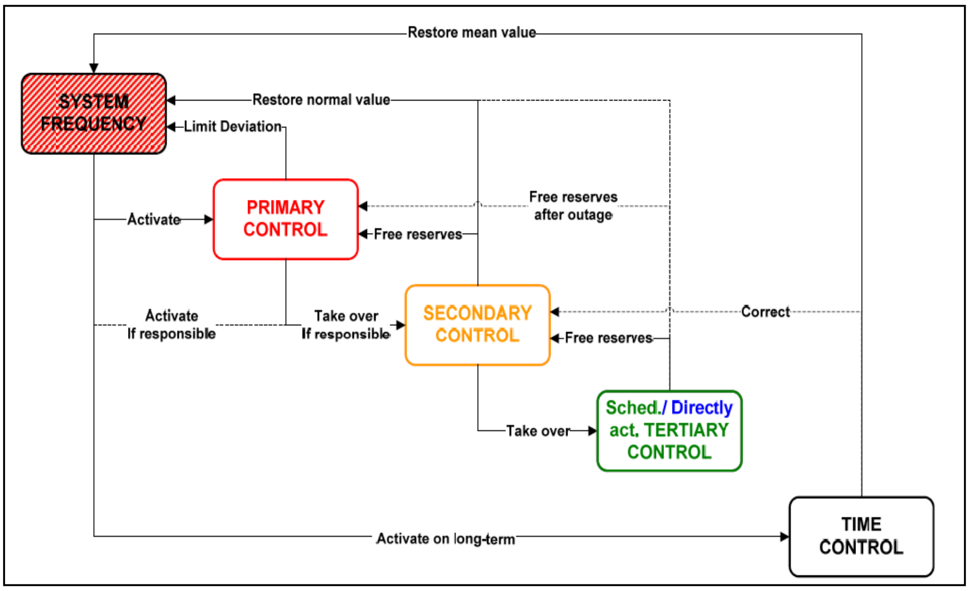

Figure 2.1. Frequency Control (ENTSO-E) [1]

2.1.2. Voltage Control or Reactive Power Control

Voltages of the busbars along the grid can be controlled by the shunt reactors or capacitors, the static VAR compensation systems and the reactive power outputs of the generating units or output voltages of the generating units. Shunt reactors/capacitors and/or static VAR compensation systems are under the control of the system operator; however, reactive power outputs or output voltages of the generating units are under the control of the power plants. The system operator regulates the voltages at all busbars by controlling the switchable shunt reactors and/or capacitors and controlling the reactive power or voltage setpoints of generating units.

Voltage control is performed in three hierarchical levels: primary, secondary and tertiary voltage control. There are two approaches around the world about the application of voltage control. In these approaches, primary and tertiary voltage control is similar in principle. The distinguishing point between these two approaches is the method of the secondary voltage control [3]. In the first approach, secondary voltage control is defined as an automatic control of the setpoints of the AVRs by a regional controller which regulates a pilot node in the region. This approach is adopted in France and Italy. On the other hand, in the second approach, the secondary voltage control is defined as the regulation of the voltage of the high voltage busbar which is the point of connection of the power plant.

2.1.2.1. Voltage Control with Regional Voltage Controllers

Overall voltage control can be arranged in three level hierarchy in this approach as can be seen in Figure 2.2. Primary voltage control is an automatic control which the voltage of generator terminal is regulated at its setpoint value. Secondary voltage control is a centralized control that regulates the setpoints of primary voltage controllers. The objective of the secondary voltage control is to manage the reactive power supports of the generators within a voltage control region. Tertiary voltage control is the manual control of setpoints for the voltages of the pilot nodes.

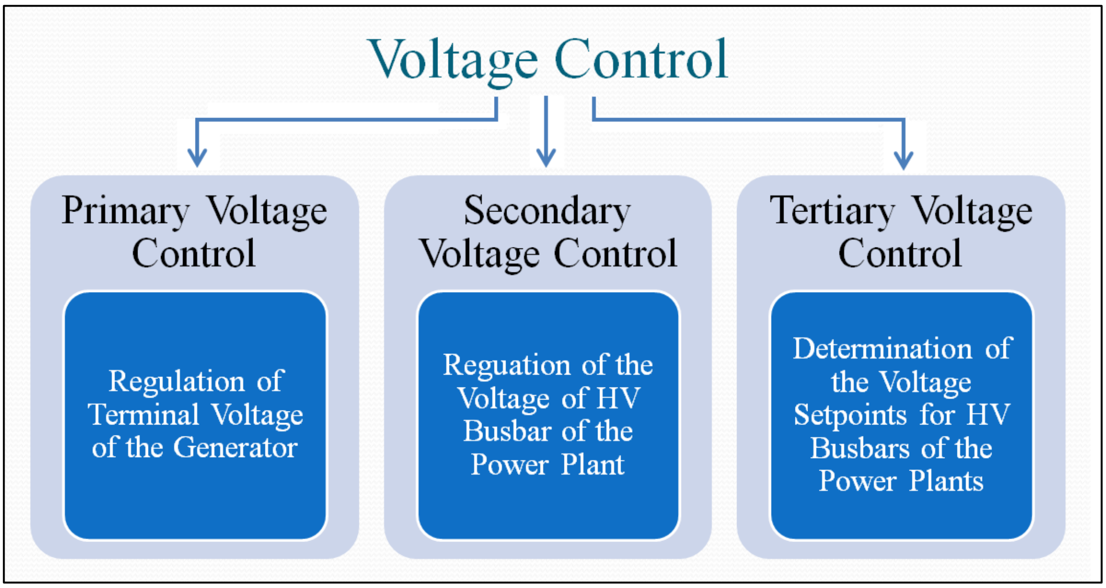

Figure 2.2. Voltage Control

In the secondary voltage control, the overall system is divided into voltage control regions and a busbar is selected as the pilot node. The automatic controller regulates the voltage of the pilot node by controlling the voltage setpoints of the primary voltage controllers within the voltage control region.

Functional block diagram of an excitation system of a synchronous generator is shown in Figure 2.3. Block 1 is the exciter which produces the excitation voltage on the field windings of the generator. Block 2 is the regulator which is the Automatic Voltage Regulator (AVR). AVR regulates the generator terminal voltage by controlling the excitation current or voltage setpoint of the exciter block. Block 3 is the voltage transducer for the terminal voltage to measure the voltage of the generator terminal. Finally, Block 4 represents the limiters and the protective circuits such as overexcitation, underexcitation limiters and etc.

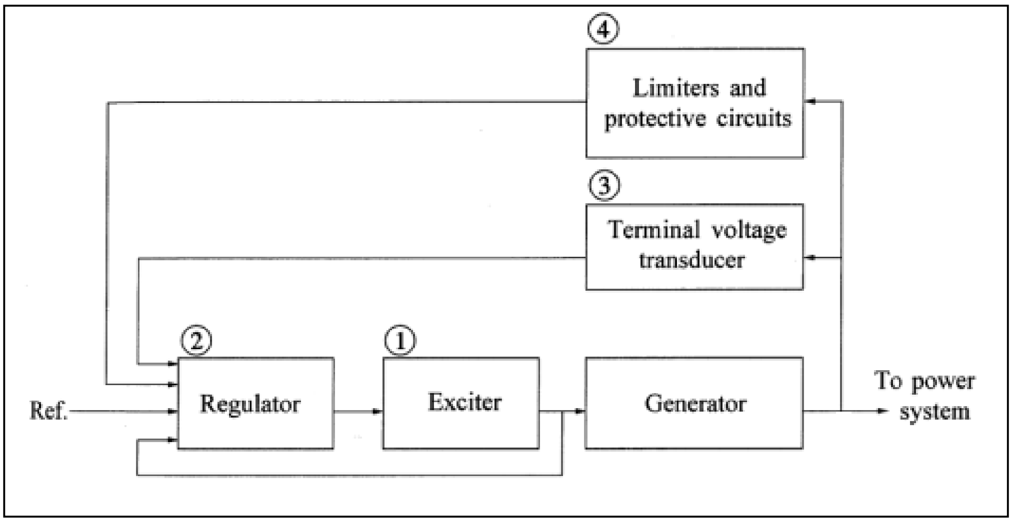

Figure 2.3. Functional Block Diagram of an Excitation System [4]

Primary Voltage Control is the control of generator terminal voltage and it is performed by the Automatic Voltage Regulators (AVRs) of the generating units. AVR regulates the generator terminal voltage according to the given voltage setpoint by controlling the excitation voltage or current of the generating unit. In case of a fault in the system near the generator, terminal voltage of the generator will decrease. In this case, the AVR will take action to increase the terminal voltage. The AVR is usually constituted as proportional integral controller, so it will increase the excitation voltage until the terminal voltage is increased to its setpoint value unless the overexcitation limit is reached. Likewise, when the terminal voltage increases, AVR will decrease the excitation voltage until the terminal voltage is decreased to its setpoint value or underexcitation limit is reached.

AVRs usually have two modes of operation. The first mode is the voltage regulation mode. In this mode, the input is the voltage setpoint for generator terminal and the AVR controls the excitation voltage/current to regulate the generator terminal current. The second mode is the reactive power regulation mode. In this mode, usually an additional controller is established. The input of this controller is the reactive power setpoint and this controller controls the voltage setpoint of the AVR to regulate the reactive power output of the generator. In the reactive power regulation mode, the second controller will change the voltage setpoint value of the first controller in order to regulate the reactive power output of the generator.

Secondary Voltage Control is the control of the voltage or reactive power setpoint values of AVRs of the generating units. It is performed automatically by regional controllers. The grid is split into regions and a pilot node is chosen for each region. Regional controllers control the voltage or reactive power setpoints of the generators in order to regulate the voltage of the pilot node according to the previously determined reference value for the pilot node. The reference value is determined by the system operator.

In Figure 2.4, the basic voltage control scheme in the approach for voltage control with regional voltage controllers is shown. The voltage setpoints for the pilot nodes are determined via central optimization. Regional controllers measure the pilot node voltage and control the setpoints of the power plant controllers in order to regulate the pilot node voltage. The power plant controller and the unit controllers are implemented inside the power plant. The power plant controller controls the setpoints of the unit controllers according to the setpoint given by the regional controller. The unit controller and the power plant controller are the elements of the primary voltage control loop. The regional controller forms the secondary voltage control while the central optimization is the tertiary voltage control.

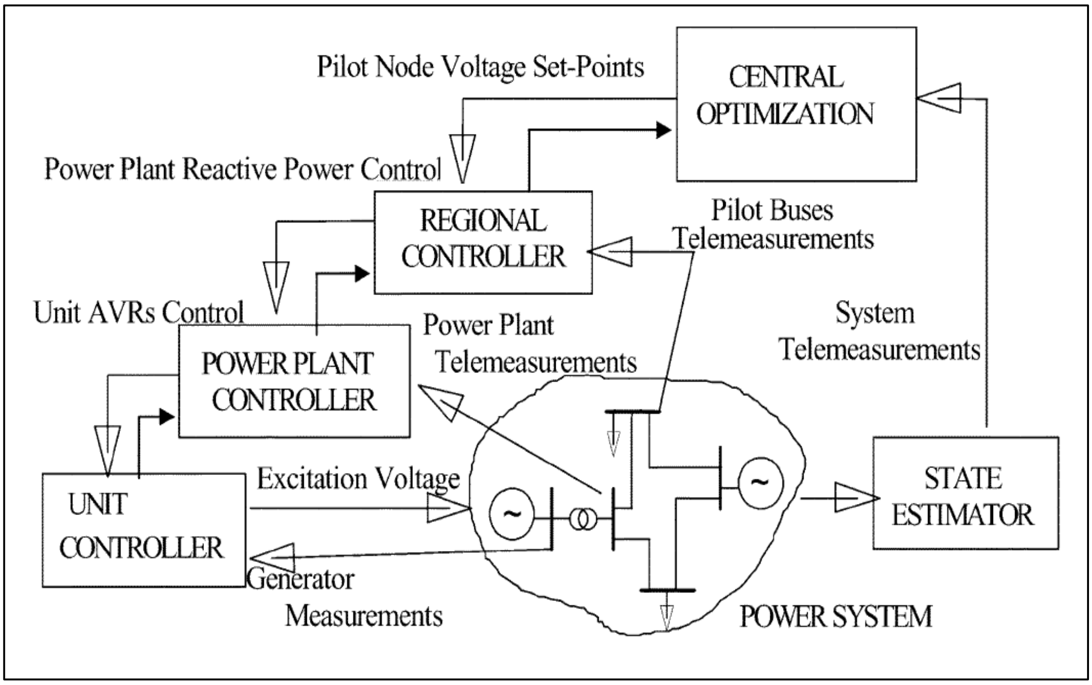

Figure 2.4. Basic Voltage Control Scheme [5]

2.1.2.2. Voltage Control with No Regional Voltage Controllers

In this approach, primary voltage control is defined as the regulation of terminal voltages by automatic voltage regulators as in the approach for voltage control with regional voltage controllers. On the other hand, the secondary voltage control is constituted as the regulation of the voltage of the high voltage busbar of the power plant. In other words, there are no regional voltage controllers for secondary voltage control in this approach. Finally, the tertiary voltage control is the determination of voltage setpoints for the high voltage busbars of the power plants. In this approach, system operator determines the voltage setpoints for the HV busbars of the power plants. Each power plant regulates the voltage of its HV busbar according to the setpoints determined by the system operator. At this point, another key subject for voltage control is the method for the regulation of the voltages of the HV busbars of the power plants. There are three main methods that the power plants can participate to the voltage control.

The first method for the regulation of the voltage of the HV busbar is the automatic regulation of the voltage of the HV busbar. The control scheme of this method is shown in Figure 2.5. In this scheme, power plants implement a HV Busbar Voltage Controller to regulate the voltage of the HV busbar. This controller is basically a proportional-integral controller which minimizes the error between the HV busbar voltage setpoint value and the measured HV busbar voltage. The controller sends a signal to increase or decrease the AVR setpoint according to the calculated error between the voltage of the HV busbar and its setpoint value. In case there is more than one units, the controller distributes the error to unit that are in service.

This method is the most efficient way for the regulation of the voltage of HV busbar. Since the voltage of the HV busbar is controlled via an automatic controller, the reaction time to a voltage disturbance at the point of connection will be faster when it is compared with the other methods. The automatic controller ensures that the voltage at the point of connection will be regulated at its setpoint value.

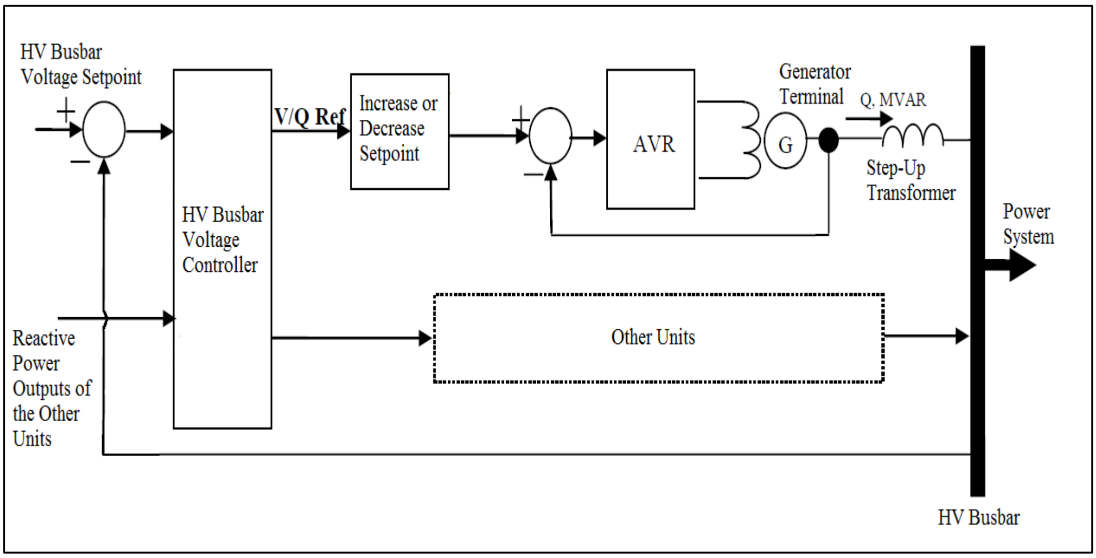

Figure 2.5. Automatic Control of HV Busbar Voltage [6]

The second method for the regulation of the voltage of the HV busbar is the manual control of the HV busbar voltage, and it is shown in Figure 2.6. In this method, an operator is responsible for the regulation of the HV busbar voltage. All the tasks which are performed by the automatic controller in the previous method are carried out by the operator manually in this method. The operator observes the voltage of the HV busbar. In case of a voltage deviation from the setpoint, the operator increases or decreases the voltage setpoint values of the AVRs of all units which are in service.

This method is slower and more risky than the first method since an operator controls the HV busbar voltage instead of a controller. In case of a voltage disturbance, an operator may react slower than a controller. Moreover, the operator could miss the voltage deviation since there is no guarantee that the operator monitors the HV busbar voltage all the time.

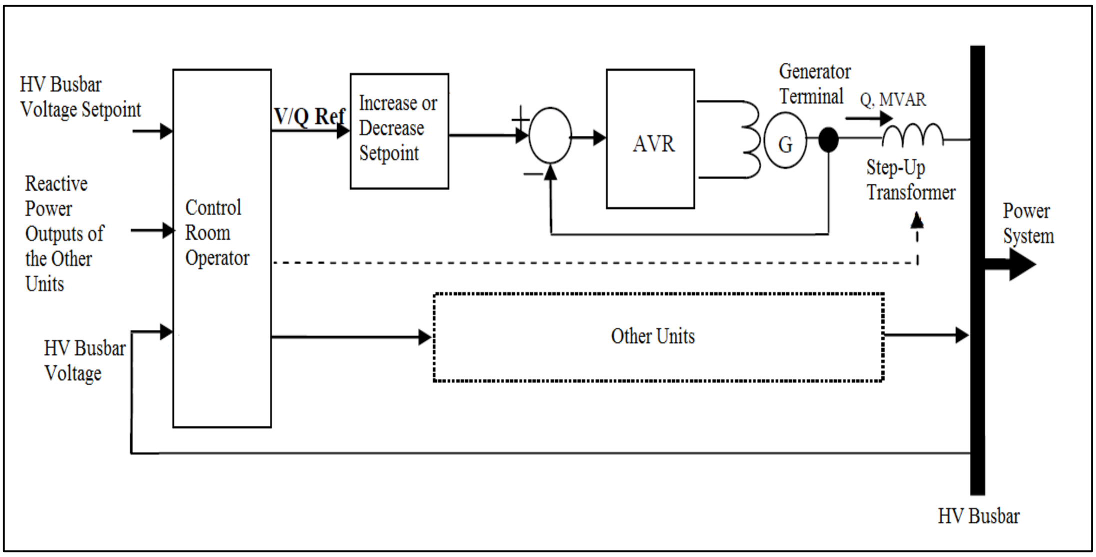

Figure 2.6. Manual Control of HV Busbar Voltage [6]

Generators usually operate between 0.95 pu and 1.05 pu terminal voltages. Beyond these limits, the operation of the generators will be jeopardized. In order to utilize more of the reactive power reserve of the generators, transformer tap positions may be used. When the generator terminal voltage limit is reached even though the reactive power limit is not reached, the terminal voltage can be increased or decreased by the help of the transformer taps. In the previous two methods for the regulation of the voltage of the HV busbar of the power plant, transformer tap positions can be used for the control of the HV busbar voltage. If the transformer has on-load tap changer, the automatic controller or the operator can use the transformer taps to regulate the HV busbar voltage.

In the previous methods, control actions of the AVRs are performed initially since the AVR is the fastest control which reacts against the voltage disturbances. Regulation of the voltage of HV busbar via an automatic controller or by an operator manually is an outer loop control. Hence, the reaction time of this secondary voltage control must be longer than the reaction time of the AVR. In the third method for the regulation of the voltage of the HV busbar, shown in Figure 2.7, these two control loops are combined to decrease the overall reaction time of these control loops.

As shown in Figure 2.7, the voltage and current measurements are obtained from the generator terminals. By using these two measurements, the voltage of the HV busbar or another point in the system can be calculated. Therefore, by adding basically a HV busbar voltage calculation block, the AVR can be converted to a controller which controls the voltage of the HV busbar. By this way, two control loops are reduced to one control loop which controls the same point faster.

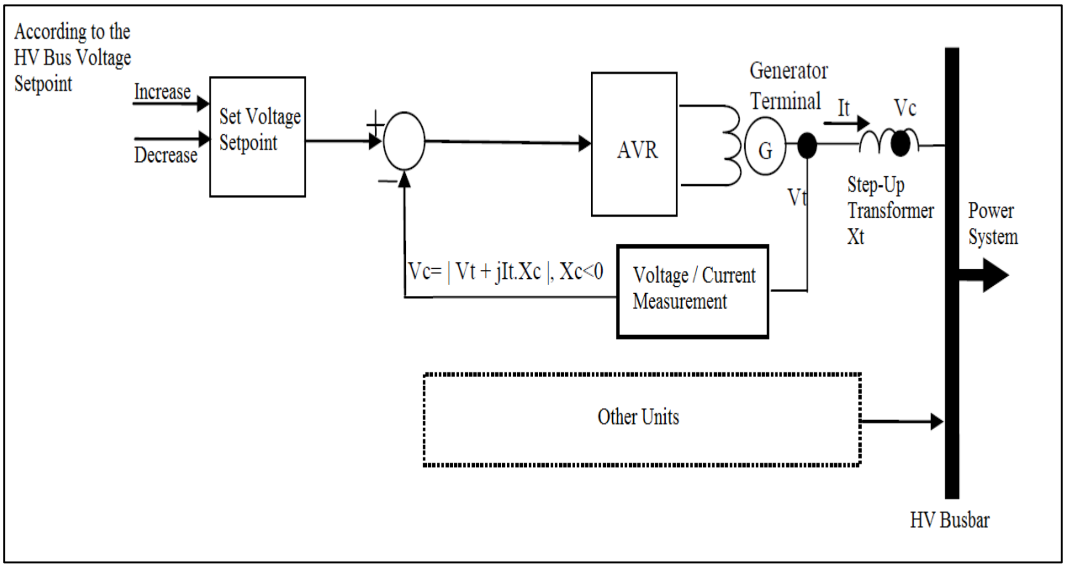

Figure 2.7. Line Drop Compensation Method [6]

However, in case there are more than one unit that are connected to the same HV busbar, voltage stability issues may arise. There may be reactive power flows between the units since all the units aim to regulate the voltage of the same point. In order to prevent these issues, the regulation points should be differed; hence, the regulation point must be pulled back for each unit. For this purpose, regulation point could be defined as a point inside the step-up transformer of each unit. As a result, when there are more than one units connected to the same HV busbar, the regulation point is defined as Vc as shown in Figure 2.7. Otherwise, the regulation point is defined as the HV busbar in this control method.

2.2. Ancillary Service Mechanism in Turkey

Before the connection with the ENTSO-E interconnected system, ancillary services were not given much importance in Turkish power system. Frequency deviation in Turkish grid was larger compared with the frequency deviation in ENTSO-E interconnected system before the interconnection with ENTSO-E system. Governors were installed in most of the generators; however, the parameters of the governors and the performance of the governors are not controlled by the system operator in detail.

By the end of 2009, studies for the ENTSO-E connection have been started [7]. During the preparation period for the ENTSO-E connection, studies about frequency and voltage control have been conducted. After the studies about the governors of the generators, the need for rehabilitation of some of the governors has been revealed. Regulations about the frequency and voltage control have been updated according to the requirements of ENTSO-E.

Turkish power grid and ENTSO-E grid have been synchronized on September 18, 2010 [7]. After the synchronization with ENTSO-E grid, frequency control applications are given much importance, because the performance index which is monitored during the trial period by ENTSO-E is mostly affected by the efficiency of frequency control applications. After the studies which are conducted about frequency control, voltage control studies have been started. In these studies, rules for procurement and monitoring of voltage control have been determined.

2.2.1. Frequency Control Mechanism

Primary frequency control is mandatory for all power plants with an installed capacity of 50 MW and above in Turkey. All generating units must have a governor for regulating their output power according to the frequency deviation. Control structure of governors is typically proportional control with a droop which is determined by TEİAŞ between 4% and 8%. All generation companies with a total installed power of 50 MW and above must provide 1% of their total installed power as primary frequency reserve. Generation companies can distribute their primary frequency reserve requirement among their generating units. In addition, generation companies may transfer their primary frequency reserve requirements to other generation companies through bilateral agreements [8].

All power plants with an installed capacity of 100 MW and above must be capable of participating in the secondary frequency control. There is a central controller, Automatic Generation Control (AGC), in National Load Dispatch Center, which controls the setpoint values for active power outputs of power plants participating in the secondary frequency control according to the frequency deviations and power exchange between Turkey and ENTSO-E interconnected system.

The power plants are categorized in three groups according to the ramp rates. In case of a power imbalance, the AGC system will activate secondary frequency reserve starting with the power plants in the first category which are the quickest power plants. If these power plants are not sufficient, the AGC system will activate the secondary reserves of other power plants [8].

2.2.2. Voltage Control Mechanism

Voltage control is performed in three hierarchical steps: primary, secondary and tertiary voltage control. All generating units with an installed capacity of 50 MW and above except the renewable units must be equipped with automatic voltage regulator

(AVR) [8]. These AVRs perform the primary voltage control actions. In case of a voltage disturbance, the AVRs regulate the generator terminal voltage via controlling the excitation system of the generator. By this way, all generating units will respond against the disturbances which change the terminal voltage of the units. When a voltage drop or voltage increase occurs in the HV busbar of a power plant, the terminal voltage will change and the AVR responds and regulates the terminal voltage.

To regulate the HV busbar voltage, a secondary mechanism is required. This mechanism is the secondary voltage control mechanism and the power plants are responsible for secondary voltage control. Power plants must regulate the HV busbar voltage at the point of connection according to the setpoint value determined by the system operator. According to the ancillary services code in effect, all power plants with a total installed power of 30 MW and above must participate in voltage control, which is referred as reactive power control in the ancillary services and grid codes.

These power plants must regulate their HV busbar voltage at the point of connection according to the setpoints determined by the system operator within a tolerance, ± 1.5% of the nominal voltage value of the HV busbar. While the power plant is regulating the HV busbar voltage, the reactive power capability of the generators must be used. No additional equipment is allowed to supply or absorb reactive power in order to regulate the HV busbar voltage. The mandatory reactive power supply is the amount that at rated active power output, the generator must be capable of supplying reactive power such that the power factor of the unit will be 0.85 lagging. The mandatory amount of the reactive power absorption from the system is that at rated active power output, the generator must be capable of absorbing reactive power such that the power factor of the unit will be 0.95 leading. The values for mandatory reactive power supply and absorption is the same for all active power output levels as the value at the rated active power output level [9]. Nevertheless, the system operator may ask for all of the reactive power capability of the generator when it is required.

In some cases, power plants can not regulate the HV busbar voltage despite that the generators reached their mandatory reactive power output level; in other words, the voltage of the HV busbar is out of limits and the reactive power outputs of the generators are at mandatory level. In that case the power plants are assumed that they are fulfilled their responsibilities [9].

Finally, tertiary voltage control is the determination of the voltage setpoints for the HV busbars of the power plants. The system operator is responsible for the operation of tertiary voltage control.

2.3. Problem Definition - Voltage Control Problem in Turkey

As mentioned earlier in this chapter, all power plants with an installed capacity of 30 MW or above except the renewable energy power plants have to participate in the voltage control. They must regulate the voltage of their high voltage terminal, which is the point that the power plant is connected to the transmission grid, according to the given voltage setpoint values. The voltage setpoint values for the power plants which are connected to 400 kV grid are determined by the operators at the National Load Dispatch Center; the voltage setpoints for other power plants are determined by the operators at the Regional Load Dispatch Centers.

The determination of these voltage setpoints is an important issue in voltage control applications. The efficiency of the voltage control hierarchy depends on this issue. If the tertiary voltage control is not defined well, there will be questions about the validity of the setpoints for the voltage at the HV busbars of the power plants. Reactive power flows through the transmission lines and the voltage profile along the grid are strongly related with the voltage setpoints of HV busbars.

When the voltage setpoints of two power plants which are electrically close to each other have been determined inattentively, there may be unnecessary extra reactive power flows in the region concerned. This will yield extra losses on transmission lines. Additionally, under heavy system load conditions, voltage drops on the long transmission lines will be larger. Hence, the voltage setpoint values for the power plants that are electrically distant to the loads should be determined sufficiently larger.

In the current application, after the determination of the active power dispatch for the power plants in the day ahead market, operators determine the voltage setpoint values for the HV busbars of the power plants. This process is based on the experiences and knowledge of the operators about the related power plants and the related region. The operators do not conduct any systematic study about the voltage profile along the grid or about the transmission losses. This may cause undesirable reactive power flows during the real time operation of the system. These extra reactive power flows increase the transmission losses.

In order to avoid these undesirable reactive power flows, a study must be conducted during the process for the determination of the voltage setpoints for the HV busbars of the power plants. Minimization of the transmission losses should be the objective of this study. In addition, the optimum voltage profile along the grid should be found at the end of this study. Finally, the voltages of all busbars considered by the system operator should be determined within the voltage limits.

Therefore, an optimization problem will be defined for the determination of the voltage setpoints for the HV busbars of the power plants. The objective function of the problem will be the minimization of the transmission losses, because when the voltage profile is optimum, the losses due to the unnecessary reactive power flows will be minimized.

The elements and parameters that affect reactive power flows will be included in the set of control variables. First of all, tap positions of the transformers have an effect on reactive power flows. The tap positions of the transformers with off load tap changers can not be changed hourly or daily, they are changed seasonally; hence only tap positions of transformers with on load tap changers will be included in the set of control variables. The other key element groups in the grid that has an effect on the reactive power flows are the switchable shunt reactors and capacitors. These elements directly insert or absorb reactive power; therefore, switchable shunt reactors or capacitors are included in the set of control variables.

Finally, the most important group is the generators. The reactive power outputs of the generators are included in the set of control variables. The active power outputs are not included since the active power dispatch data are determined in the day ahead market.

The constraints of the optimization problem will be the power flow equations since the objective is to minimize the transmission losses and find an optimum voltage profile along the system. In addition to the power flow equations, voltage limits for the busbars concerned by the system operator and the reactive power limits of the generators will be included in the constraints.

The voltages of the busbars within 154 kV and 400 kV grid are taken into consideration. The voltage limits for these busbars are defined as ±10% of its nominal value in Turkish grid code and IEC 60038 standards [8] [10]. Nevertheless, the voltage limits are set to ±5% of the nominal voltage value of the busbar, and ±5% is reserved as a security margin. By this way, it is ensured that the voltages of the busbars are maintained between ±10% limits of the nominal voltage in case of the voltage disturbances.

There are some cases that the optimum voltage profile can not be found with the previously determined voltage limits, 0.95 pu minimum voltage limit and 1.05 pu maximum voltage limit. In those cases, additional reactive power absorption or supply is required in order to find an optimum voltage profile within the voltage limits. The need for the additional reactive power absorption or supply can be satisfied by the power plants. The power plants that are in service can supply or absorb the additional reactive power by decreasing their active power output levels; on the other hand, the power plants that are not dispatched at that time can supply or absorb the additional reactive power by the redispatch of these power plants. The important issue here is that the electrical distance between the generators and the busbars whose voltages are out of limits affects the amount of additional reactive power.

In order to determine the source of the additional reactive power absorption or supply, a second optimization problem is required. In the second optimization problem, the objective is to minimize the cost of redispatch of active power levels of the power plants in order to supply or absorb additional reactive power. The changes in active power levels of the power plants are included in the set of control variables of the second optimization problem. The constraints consist of the effects of the generators to the busbars whose voltages are out of limits.

In this thesis study, an algorithm is developed for the solution of these two optimization problems. The algorithm will be defined in detail in the next chapters. The algorithm for the solution of these optimization problems is developed and executed in a power system analysis software, DigSilent PowerFactory and a technical computing software, Matlab. The algorithm consists of two stages which are for the solution of the two optimization problems.

Stage I of the algorithm which is for the first optimization problem is developed using DigSilent since the first problem includes Optimal Power Flow, and DigSilent offers useful tools for solving this problem such as OPF Solving Tool and Network Reduction Tool. On the other hand, Stage II, which is for the second optimization problem, is developed using Matlab since the Matlab offers a good platform for the solution of optimization problems. During the process for the determination of the voltage setpoints for the HV busbars of the power plants, Stage I will be executed initially for each hour. In this stage, the optimum voltage profile will be found by using OPF solution tool in DigSilent. If the optimum voltage profile is found without any voltage limit violations for an hour, the calculated voltage values of HV busbars of the power plants are assigned as the voltage setpoints for that hour. If voltage limit violations occur, Stage II will be executed and the redispatch for the additional reactive power will be determined. After the execution of Stage II, Stage I will be executed again with the new active power dispatch data. These two stages will be executed iteratively until the optimum voltage profile without any voltage limit violations has been reached for each hour. When the optimum voltage profile without any voltage limit violation has been reached, the calculated voltage values of HV busbars of the power plants will be assigned as voltage setpoints for that hour.

CHAPTER 3

SYSTEM MODELING AND THE ALGORITHM FOR DETERMINATION OF VOLTAGE SETPOINTS FOR HIGH VOLTAGE BUSBARS OF THE POWER PLANTS

3.1. Modeling the Grid Elements

The main components of a modern power system are generating units, transformers, transmission lines and loads. Most of the generating units are the synchronous generators which can supply active and reactive power to the system. Transformers are the key components of a power system since they provide the connection between different voltage levels along the system. Transmission lines are the components for the transmission of the power. Loads can be fronted in various forms. Synchronous and asynchronous motors, resistive, capacitive and inductive loads are some of these forms of the loads.

The raw data of the system used in this thesis study, are obtained from TEİAŞ. The raw data are utilized to build the system model in DigSilent. The parameters of the generator step-up transformers and the reactive capability limits of the generators with an installed capacity of 30 MW and above are updated according to the manufacturers' datasheets. In addition, the parameters of the autotransformers and the loads are updated in accordance with the load statistics of Turkish power system and the transformer data which are obtained from TEİAŞ.

The system model of West Anatolia Region is used for this thesis study, and it is built via the network reduction methods. There are two network reduction methods in DigSilent; namely, network reduction for load flow and network reduction for short circuit calculations. Since load flow equations are present as constraints in Optimal Power Flow problem; network reduction for load flow is adequate for this thesis study. The software puts three load flow equivalent models into use for the network reduction tool; load equivalent, ward equivalent and extended ward equivalent. The system model of West Anatolia Region has been reduced via Network Reduction Tool using the Extended Ward Equivalent Model at the boundaries.

The required generator data are nominal apparent power, nominal voltage, active and reactive power limits of the generator and the active power dispatch. Apparent power and active power dispatch data are obtained directly from TEİAŞ. Active and reactive power limits of the generators have been updated according to the manufacturers' datasheets during the data preparation period for the thesis study.

The required transformer data are nominal power, short circuit impedance, and nominal HV and LV voltage values and the tap changer data. Tap changer data of the autotransformers have been obtained from TEİAŞ and used in the system model. Also the step-up transformer data have been revised together with the generator data.

The required data for the transmission line models are nominal voltage, nominal current and resistance and reactance data. The equivalent circuits for the transmission lines are modeled as PI-circuit equivalent. All the data are taken from TEİAŞ.

The required load data are active and reactive power consumptions and voltage dependency parameters. Active and reactive power demand data are obtained from TEİAŞ. Voltage dependency parameters have been calculated according to the given load statistics of Turkish power system. West Anatolia Region is split into 6 areas and the voltage dependency parameters have been calculated according to the load distribution of these 6 areas. Loads are classified in 6 types which are residential loads, commercial loads, industrial loads, agricultural loads, illumination loads and the other loads. Typical load characteristics are used for these types [10]. Load distribution for the areas is given in Table 3.1.

Table 3.1. Load Distribution in West Anatolia Region

Area	Residential Loads (%)	Commercial Loads (%)	Industrial Loads (%)	Agricultural Loads (%)	Illumination Loads (%)	Other Loads (%)
Çanakkale	10.52	4.06	80.46	0.83	1.38	2.75
Balıkesir	33.11	13.18	35.16	1.43	4.69	12.42
İzmir	26.51	11.65	53.40	1.95	0.82	5.67
Manisa	30.25	10.39	39.61	8.32	2.22	9.21
Aydın	43.35	18.03	22.37	3.38	3.13	9.74
Muğla	36.92	32.82	8.76	1.29	2.03	18.20

Six new loads are connected to each point where the loads are connected. Each of these six loads represents the six different load types. The active and reactive power demands of the original load are distributed to these loads according to the statistics of the area which the load is in. In addition, active and reactive power demands of each load are modeled as in Equation 3.1. The e_{aP} and e_{aQ} parameters of each type are given in Table 3.2.

$$P = P_0\left(\frac{V}{V_0}\right)^{e_{aP}} \qquad (3.1)$$

$$Q = Q_0\left(\frac{V}{V_0}\right)^{e_{aQ}}$$

P_0 : Active power demand of the load at 1 pu voltage

Q_0 : Reactive power demand of the load at 1 pu voltage

e_{aP} : Voltage dependency factor for active power demand of the load

e_{aQ} : Voltage dependency factor for reactive power demand of the load

Table 3.2. Voltage Dependency Parameters for Load Types

	e_{aP}	e_{aQ}
Residential Loads	1.5	2.8
Commercial Loads	0.7	2.5
Industrial Loads	0.1	0.6
Agricultural Loads	1.4	1.4
Illumination Loads	1.5	2.7
Other Loads	0	0

3.2. Overall View of the Algorithm for Determination of Voltage Setpoints for High Voltage Busbars of the Power Plants

The aim of this study is to determine the voltage setpoints of the power plants by optimizing the voltage profile along the grid and maintaining the voltages of the busbars within an acceptable region. The reactive power limits of the generators are the other important parameters to take into consideration.

An algorithm with two stages has been developed for the solution of the voltage control problem in Turkey. These stages are for the voltage profile optimization and for the minimization of the cost of corrective actions to insert extra reactive power to the system when it is required. Stage I has been developed using DigSilent and it is executed with the system model of West Anatolia Region. Stage II has been developed using Matlab and this stage uses the data of the price offers for 1 MW increase and 1 MW decrease in output powers of the power plants. Stage I is executed for all hours while Stage II is executed when required; in other words, when voltage problem at some busbars are not resolved at the end of Stage I.

In Stage I, optimum voltage profile is determined; however, the desired voltage limits for the busbars, which are 1.05 pu and 0.95 pu, are not taken into consideration. For this reason, at the end of Stage I which is executed using DigSilent, the voltages of all busbars are checked whether they are out of the desired limits or not. In a case that all voltages of busbars are between the desired limits, Stage I has resolved the voltage control problem completely for that hour. On the other hand, if there are some busbars whose voltages are out of the desired limits, Stage I can not find a feasible solution for the voltage setpoints of the power plants. In order to resolve the issue, extra reactive power is required. For this purpose, Stage II which is developed using Matlab will be executed. In this stage, the redispatch of power plants to get extra reactive power which makes all the voltages of busbars are between the desired limits, is determined.

In the first iteration of Stage II in Matlab, busbars, whose voltage values are out of the desired limits, are assumed to be appearing in a region such that all problematic busbars are electrically close to each other. Hence, voltage sensitivities of the generators to the busbar with the extreme voltage constitute the constraints. The results of the redispatch optimization in Matlab will be transferred to DigSilent and Stage I in DigSilent will be executed again in order to check whether the voltage problems in all busbars are resolved or not. If the problem still continues; in other words, if there are still busbars whose voltages are out of the desired limits, Stage II in Matlab will be executed but this time problematic busbars are assumed to appear in two electrical regions. Hence, voltage sensitivities of generators are calculated for two busbars and constraints are constituted accordingly. For the case which the voltage problems can not be solved in two iterations, voltage sensitivities of generators for additional problematic busbar will be included in the constraints. This loop will be stopped when voltages of all busbars occurs within the desired limits.

The active power dispatch data and the topology data are for the day which summer peak demand occurred. When Stage I in DigSilent is executed, voltage problems are occurred in one region that is the south side of West Anatolia grid. In order to simulate the case which the problematic busbars appear in more than one region, the system data are altered to create extra voltage problems. For this purpose, a shunt reactor is connected to a 154 kV busbar in the west side of the grid. By this way, two operation scenarios are defined for the simulations. In the first operation scenario, low voltage problems occur in south side of the grid. In the second operation scenario, low voltage problems occur in two regions, south side and west side of the grid.

CHAPTER 4

VOLTAGE PROFILE OPTIMIZATION ALONG THE GRID AND MINIMIZATION OF THE COST OF CORRECTIVE ACTIONS

The determination of the voltage setpoint values for high voltage busbars of power the plants are obtained through an algorithm which has two stages. Stage I is the basis for the algorithm which the voltage setpoint values for the HV busbars are determined. In Stage I, voltage profile along the grid is optimized. Stage II of the algorithm has a supporting role for the algorithm. When the voltage profile optimization in Stage I can not find a solution with the voltages lie within the desired limits, Stage II of the algorithm which is minimization of the cost of corrective actions is executed.

When extra reactive power generation is required to develop an optimum voltage profile in a network without any voltage limit violations, the system operator is entitled to request extra reactive power from a generating unit by decreasing the active power output of the generator [8]. In addition, the system operator may also take a power plant into service to get the reactive power in that region. The main problem is how the system operator determines the amount of this extra reactive power or which option should be used to get this extra reactive power.

Stage I of the algorithm which is the voltage profile optimization is developed using DigSilent where Stage II which is the minimization of the cost of correctional actions is developed using Matlab. The details of these stages are discussed in this chapter.

4.1. Optimization of Voltage Profile Along The Grid

The first step in the overall algorithm for the determination of the voltage setpoints for power plants is the voltage profile optimization studies. These studies are conducted in DigSilent. While the setpoints for the power plants are determined, it is desired to achieve an optimum voltage profile along the system. One of the important issues in these studies is that it is undesirable to have reactive power injections which are counteracting each other. In other words, it is not desired that a generator injects reactive power into the system while another nearby generator absorbs reactive power from the system. Another goal of these studies is the minimization of the transmission losses. The last objective of this study is to maintain all voltages within the desired limits.

For this purpose, optimal power flow (OPF) method is used. OPF is usually used for economic dispatch problems. OPF for economic dispatch problem is basically an optimization problem in which the objective function is the minimization of total generation cost for the generators. The control variables are the active power outputs of the generators and the constraints are the power flow equations. By this way, power flow equations are satisfied while the cost is minimized. On the other hand, OPF is used for voltage profile optimization problem. In this case, the objective function is the minimization of transmission losses, so the transmission losses will be minimized at the end of the solution. The control variables are the reactive power injections of the generators, since the active power dispatch is determined in the day ahead market. Additionally, the switchable shunts and transformer tap positions are the other control variables, since these variables affect the voltage profile along the system. Finally, the constraints are power flow equations, reactive power limits of the generators and voltage limits of the busbars. In DigSilent, OPF is solved by an internal tool which is built on power flow calculations and the solution method of the optimization problem is the AC optimization based on an interior point algorithm.

The objective function of the OPF problem, the control variables and the constraints are explained in the previous paragraph. However, the OPF tool is not sufficient by itself for the determination of voltage setpoint values for the power plants. There are some cases that additional measures are required to have an optimum voltage profile with all voltages maintain within the desired limits. In other words, for some cases, the OPF tool can not find a feasible solution with the specified voltage limits for busbars which are 1.05 pu and 0.95 pu. Therefore, the algorithm, whose flowchart is shown in Figure 4.1, has been developed using DigSilent.

First of all, the active power output levels of the power plants are updated according to the active power dispatch data which are determined in the day ahead market. Secondly, before the execution of the OPF tool, the voltage limits at all busbars are set to give a wide margin such as *Vmax* is set to 1.2 pu and *Vmin* is set to 0.8 pu. These limits are set wide because in some cases, the OPF tool can not find a solution between the limits of 0.95 pu and 1.05 pu. After the update in voltage limits, OPF tool is executed in order to achieve an optimum voltage profile along the system.

If the OPF does not converge and there is no feasible solution, the voltage limits will be widened in steps until the OPF is converged. Otherwise, voltage limits will be narrowed down to the desired limits specified as 0.95 pu and 1.05 pu iteratively. In each iteration, OPF calculations will be repeated to check if there is a solution with the current limits. If the voltage limits are narrowed down to 0.95 pu and 1.05 pu without any constraint violations, as a result of this stage, a feasible optimum solution has been reached with the desired voltage limits for the busbars. The voltage profile is optimized and there is no need for additional measures. In this case, the calculated voltages of busbars at the point of connection of the power plants will be assigned as high side voltage setpoint values for power plants.

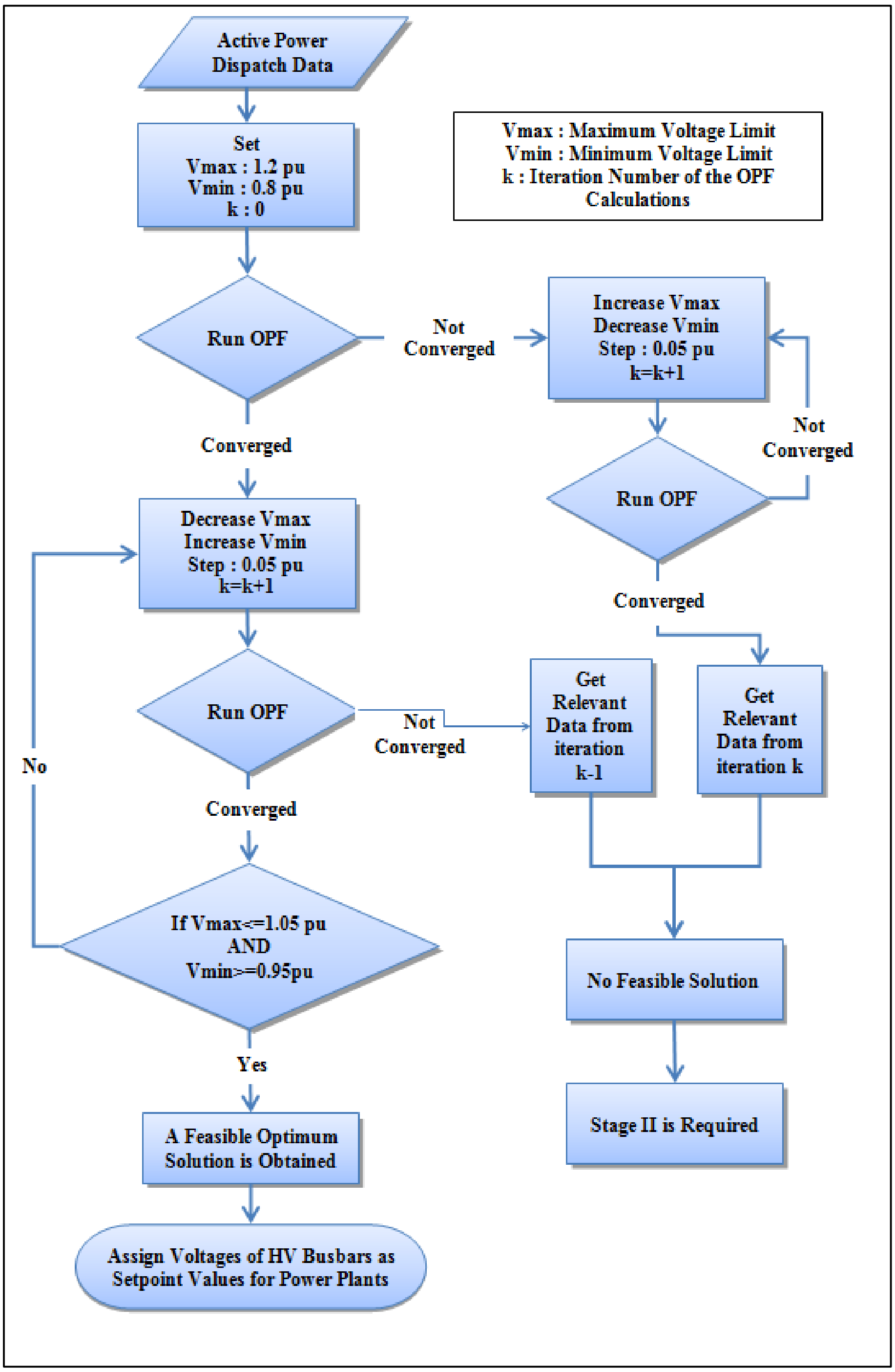

Figure 4.1. Flowchart of the Stage 1

The parameter *k*, as an iteration counter, is defined in Stage I to keep the track of the results of the OPF calculations. At the beginning of Stage I, the iteration counter *k* is set to zero. For each OPF calculation, the value of the parameter *k* is increased. Stage I of the algorithm is terminated at three conditions. The first condition, as stated previously, is the condition that a feasible optimum solution has been reached with the desired voltage limits. In this case, the calculated voltage values as the result of the latest OPF calculation will be assigned as the voltage setpoint values for the power plants. The second condition is the condition that the OPF converge with the voltage limits wider than the initial voltage limits, i.e. 1.2 pu and 0.8 pu. If the OPF does not converge with the initial voltage limits, the voltage limits will be widened step by step until the OPF converges. In this case, the voltage limits for the busbars, voltage sensitivity data and the results of the latest OPF calculation will be transferred to the Matlab for Stage II. Finally, the third condition is the condition that the OPF does not converge in the loop where the voltage limits are narrowed. In this case, as for the second condition, the voltage limits for the busbars, voltage sensitivity data and the results of the OPF calculation at iteration *k*-1 will be transferred to the Matlab for Stage II. In the cases when the OPF does not converge, the optimum voltage profile found by the OPF tool is not sufficient for the overall solution since the desired voltage limits are not satisfied. To find the optimum voltage profile with the desired limits satisfied, additional reactive power injection or absorption is required. To determine the power plants which inject or absorb reactive power, Stage II of the solution algorithm for the minimization of the cost of corrective actions will be executed using Matlab.

4.2. Minimization of the Cost of Corrective Actions

The flowchart presented in Figure 4.2, is Stage II of the overall algorithm developed using Matlab in order to find the economically optimum redispatch of the power plants. The need for the redispatch is resulted from the need for additional reactive power to maintain the voltages of all busbars concerned within the desired limits.

Initially, the voltage sensitivities of the generators to the problematic busbars are exported from DigSilent to be used in Stage II of the solution algorithm which is developed using Matlab. The contributions of the generators to the correction of the voltage of the problematic busbars are represented as constraints by the help of the voltage sensitivity data.

For the first iteration of Stage II, the problematic busbars are assumed to be electrically close to each other; hence, only one busbar is selected for the correction of its voltage. Stage II of the solution algorithm is executed iteratively until the voltage limit violations are cleared. In each iteration, the assumption about the locations of problematic busbars is updated and the number of regions in which the problematic busbars lie is increased one by one. In the first iteration of Stage II, the busbar whose voltage is minimum or maximum is selected for correction. In the next iterations, the busbars are selected such that the electrical distance to each other will be maximum.

After the selection of the busbars, the effects of the generators to the selected busbars will be included in the constraints as will be described later in this chapter. The minimization problem of the cost of corrective actions has a piecewise continuous objective function; hence, the linear programming methods are not sufficient for the solution. For this reason, the optimization problem will be converted to a Mixed Integer Linear Programming (MILP) problem. Finally, the converted problem will be solved and the final redispatch data will be exported in order to be used in the voltage profile optimization problem in DigSilent.

The aim of Stage II is to find the most economic redispatch solution to make all the voltages remain between the desired limits. In the first iteration of this stage, it is assumed that all busbars with voltage limit violation are electrically close to each other. With this assumption, when the voltage problem of the busbar with the extreme voltage value is solved, all voltage problems will be solved. For that reason, voltage problem of only one busbar will be included in the constraints in the first iteration of this stage.

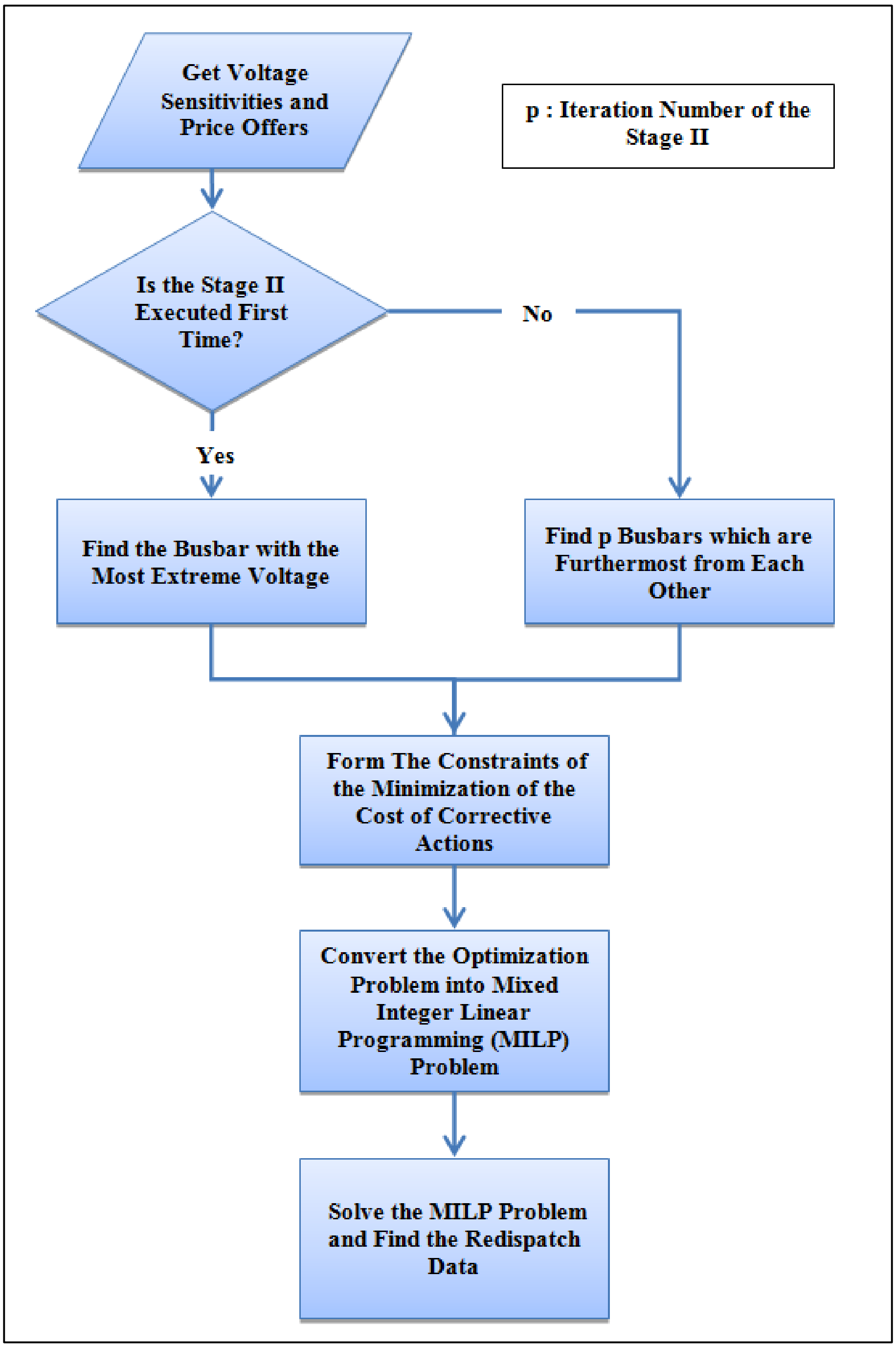

Figure 4.2. Flowchart of the Stage 2

If the voltage problem of all busbars can not be solved in the first iteration of Stage II of the algorithm, and there are busbars whose voltages are out of limits; Stage II will be executed again. This time, it is assumed that the voltage problem occurs in two electrical regions. Therefore, voltage problem of two busbars will be included in the constraints in this iteration of Stage II. These two busbars will be selected in a way that the electrical distance between these two busbars will be maximum. If the voltage problem can not be solved in these two iterations of the algorithm, Stage II will be executed iteratively until the voltage problem of all busbars is solved and in every iteration, voltage problem of an additional busbar will be included in the constraints of the optimization problem.

The problem will be:

$$\begin{gathered} \min f = \sum_{i=1}^{m} f_i + \sum_{j=1}^{n} f_j \\ such\ that\ \boldsymbol{M} \cdot \Delta \boldsymbol{P} \leq V \end{gathered} \tag{4.1}$$

where

$$f_i = \begin{cases} CLoadInc_i \cdot \mathit{\Delta} P_i \ if\ \mathit{\Delta} P_i \geq 0 \\ CLoadDec_i \cdot \mathit{\Delta} P_i \ else \end{cases}$$

$$f_j = MSGL_j CLoadInc_j Status_j$$

$$\boldsymbol{M} = \begin{bmatrix} \frac{dVbus_1}{dP_1} & \cdots & \frac{dVbus_1}{dP_i} & \cdots & \frac{dVbus_1}{dP_{m+n}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{dVbus_k}{dP_1} & \cdots & \frac{dVbus_k}{dP_i} & \cdots & \frac{dVbus_k}{dP_{m+n}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{dVbus_t}{dP_1} & \cdots & \frac{dVbus_t}{dP_i} & \cdots & \frac{dVbus_t}{dP_{m+n}} \end{bmatrix}$$

$$\Delta \boldsymbol{P} = \begin{bmatrix} \Delta P_1 \\ \vdots \\ \Delta P_i \\ \vdots \\ \Delta P_m \\ MSGL_1 \cdot Status_1 \\ \vdots \\ MSGL_j \cdot Status_j \\ \vdots \\ MSGL_n \cdot Status_n \end{bmatrix}$$

m : Number of power plants which are in service

n: Number of power plants which are out of service

t : Execution number

CLoadInc$_i$ *(TL/MW)* : Price Offer per 1 MW increase in output power of power plant *i* which is in service.

CLoadDec$_i$ *(TL/MW)* : Price Offer per 1 MW decrease in output power of power plant *i* which is in service.

CLoadInc$_j$ *(TL/MW)* : Price Offer per 1 MW increase in output power of power plant *j* which is out of service.

ΔP_i *(MW)* : The amount of change in output power of power plant *i* which is in service.

$dVbus_k/dP_i$ *(1/MW):* The pu increase in the voltage of bus *k* when the active power output of the generator *i* is increased 1 MW.

$MSGL_j$ *(MW)* : Minimum stable generation level

$Status_j$ *(binary)* : Status of power plant j which is out of service.

1 : In service

0 : Out of service

The objective function of this problem is to minimize the cost of redispatch of power plants. The cost function is constituted of two parts. The first part, $\sum_{i=1}^{m} f_i$, is the sum of the cost functions for the redispatch of the power plants that are in service. The second part, $\sum_{j=1}^{n} f_j$, is the sum of the cost functions for the redispatch of the power plants that are out of service.

$$f_i = \begin{cases} CLoadInc_i \cdot \Delta P_i \ if \ \Delta P_i \geq 0 \\ CLoadDec_i \cdot \Delta P_i \ else \end{cases}$$

$$f_j = MSGL_j CLoadInc_j Status_j$$

The price offers of the power plants for 1 MW increase, $CLoadInc_i$, and 1 MW decrease, $CLoadDec_i$, are not equal to each other. Therefore, cost function of a power plant that is in service, f_i, will be piecewise continuous. On the other hand, since there will be only the increase offer of the power plants that are out of service, the cost function of these power plants will not be piecewise.

In addition, since a power plant has a minimum stable output level ($MSGL_j$) and if a power plant redispatches and is asked to be in service, the amount of the increase in the output power will be the minimum stable output level. Therefore, in the cost function of the power plants that are out of service, there will be a binary variable ($Status_j$).

If the voltage of a busbar is out of the desired limits after the voltage profile optimization in DigSilent; extra reactive power is required in order to change the voltage of this busbar. Either the active power output of the power plants in service is decreased or new power plants that are not dispatched initially are taken into service to get reactive power of them.

The number of iterations of Stage II at each hour is equal to the number of problematic busbars whose voltages will be corrected. Hence, if the second and next iterations of Stage II are required, the number of problematic busbars considered in the constraints will be more than one, and each of these busbars will be represented as bus *k*. The constraints of this optimization problem consist of the effects of the power plants to the problematic busbars. To represent these effects, the voltage sensitivity factors will be used. The voltage sensitivity factor $dVbus_k/dQ_i$ for each busbar and the power plant, is calculated using DigSilent. In order to get extra reactive power from a power plant that is in service; the active power output must be decreased according to its reactive power capability curve. The factor dQ_i/dP_i for each power plant will be calculated according to its active power output level and reactive power capability curve. As a result; the constraint for this optimization will be:

$$\sum_{i=1}^{m} \frac{dVbus_k}{dQ_i} \cdot \frac{dQ_i}{dP_i} \cdot \Delta P_i + \sum_{j=1}^{n} \frac{dVbus_k}{dQ_j} \cdot \frac{dQ_j}{dP_j} \cdot MSGL_j \cdot Status_j \leq \begin{cases} Vbus_k - V_{min} \ , \ Vbus_k < V_{min} \\ V_{max} - Vbus_k \ , \ Vbus_k > V_{max} \end{cases} \tag{4.2}$$

$dVbus_k/dQ_i$ (1/MVAr): The pu increase in the voltage of bus *k* when the reactive power output of the generator *i* (in service) is increased 1 MVAr.

$dVbus_k/dQ_j$ (1/MW): The pu increase in the voltage of bus *k* when the reactive power output of the generator *j* (out of service) is increased 1 MVAr.

dQ_i/dP_i (MVAr/MW): The ratio of the change of the reactive power output to the change of active power output for the generators in service.

dQ_j / dP_j *(MVAr/MW)*: The ratio of the change of the reactive power output to the change of active power output for the generators in service

ΔP_i *(MW)*: The amount of change in output power of power plant *i* which is in service.

$MSGL_j$ *(MW)* : Minimum stable generation level

$Status_j$ *(binary)* : Status of power plant *j* which is out of service.

1 : In service
0 : Out of service

m : Number of power plants which are in service

n: Number of power plants which are out of service

Since the cost function is assumed to be piecewise continuous, the original problem can not be solved by linear optimization problem methods; hence, the problem will be converted to a mixed integer linear programming(MILP) problem.

4.3. Conversion of the Optimization Problem into a MILP Problem

In order to represent the piecewise continuous cost function of the original problem; new control variables will be defined. For each variable ΔP_i, which is the amount of change in the output power of power plant *i* that are in service; 2 new variables will be introduced: a real variable z_i and a binary variable δ_i [11].

$$\delta_i = \begin{cases} 1 \, , if \; \Delta P_i \geq 0 \\ 0 \, , else \end{cases} \tag{4.3}$$

$$z_i = \begin{cases} CLoadInc_i \cdot \Delta P_i \, , & \Delta P_i \geq 0 \\ CLoadDec_i \cdot \Delta P_i \, , & else \end{cases} \tag{4.4}$$

Hence;

$$if\ \delta_i = 1\ ,\ z_i = CLoadInc_i \cdot \Delta P_i$$
$$if\ \delta_i = 0\ ,\ z_i = CLoadDec_i \cdot \Delta P_i$$

With the additional variables; the new objective function will be:

$$\min \boldsymbol{K^T} \cdot \boldsymbol{X}$$

$$\boldsymbol{K} = \begin{bmatrix} 1 \\ \vdots \\ 1 \\ 0 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ 0 \\ MSGL_1 \cdot CLoadInc_1 \\ \vdots \\ MSGL_n \cdot CLoadDec_n \end{bmatrix} \qquad \boldsymbol{X} = \begin{bmatrix} z_1 \\ \vdots \\ z_m \\ \Delta P_1 \\ \vdots \\ \Delta P_m \\ \delta_1 \\ \vdots \\ \delta_m \\ Status_1 \\ \vdots \\ Status_n \end{bmatrix} \tag{4.5}$$

$$K^T \cdot X = \sum_{i=1}^{m} z_i + \sum_{j=1}^{n} MSGL_j \cdot CLoadInc_j \cdot Status_j$$

Finally, for each f_i , the cost function of a power plant in service; 6 new constraint inequalities will be introduced [11].

$$\begin{gathered} D_i \cdot \delta_i \leq \Delta P_i + D_i \\ d_i \cdot \delta_i \leq -\Delta P_i \\ (M_{2i} - m_{1i}) \cdot \delta_i - z_i + CLoadInc_i \cdot \Delta P_i \leq M_{2i} - m_{1i} \\ (M_{1i} - m_{2i}) \cdot \delta_i + z_i - CLoadInc_i \cdot \Delta P_i \leq M_{1i} - m_{2i} \\ (m_{2i} - M_{1i}) \cdot \delta_i - z_i + CLoadDec_i \cdot \Delta P_i \leq 0 \\ (m_{1i} - M_{2i}) \cdot \delta_i + z_i - CLoadDec_i \cdot \Delta P_i \leq 0 \end{gathered} \tag{4.6}$$

Where

$$\begin{aligned} D_i &= -\Delta P_{imin} \\ d_i &= -\Delta P_{imax} \\ M_{1i} &= \Delta P_{imax} \cdot CLoadDec_i \\ M_{2i} &= \Delta P_{imax} \cdot CLoadInc_i \\ m_{1i} &= \Delta P_{imin} \cdot CLoadDec_i \\ m_{2i} &= \Delta P_{imin} \cdot CLoadInc_i \end{aligned} \tag{4.8}$$

When the change in the output power of a power plant is positive; in other words, load increase order is given to the power plant; the value of the additional binary variable δ_i will be ‘1’ and the constraints will become:

$$\begin{gathered} 0 \leq \Delta P_i \leq \Delta P_{imax} \\ z_i = CLoadInc_i \cdot \Delta P_i \\ \Delta P_{imin} \cdot CLoadInc_i < z_i \\ z_i < \Delta P_{imax} \cdot CLoadInc_i \end{gathered} \tag{4.9}$$

Likewise, when the change in the output power of a power plant is negative; load decrease order is given to the power plant, the value of the additional binary variable δ_i will be ‘0’ and the constraints will become:

$$\begin{gathered} \Delta P_{imin} \leq \Delta P_i \leq 0 \\ z_i = CLoadDec_i \cdot \Delta P_i \\ \Delta P_{imin} \cdot CLoadDec_i < z_i \\ z_i < \Delta P_{imax} \cdot CLoadDec_i \end{gathered} \tag{4.10}$$

Finally, the number of new constraint inequalities will be six times the number of power plants which are in service in addition to the constraint inequalities which represent the contributions of the power plants to the voltages of the problematic busbars.

CHAPTER 5

SIMULATION RESULTS AND DISCUSSION

The details of the algorithm that is developed to provide a solution for the voltage control issue in Turkey are explained in the previous chapters. In this chapter, the verification of this algorithm will be done. In order to verify the algorithm, it is implemented and applied to a real system. Realization studies of the system model and verification of the algorithm is performed by using DigSilent and Matlab.

Voltage is a regional index; in other words, voltage problem in a region can not be solved by taking actions in an electrically far region. If the Turkish grid is considered, a voltage problem in the west side of the grid can not be solved by the actions taken in the east side of the grid. In addition, the 154 kV grid is split according to the areas of responsibilities of the regional dispatch centers. In other words, the breakers between different regions at the 154 kV level are opened. The connection between the 154 kV grids is provided through the 400 kV grid. Therefore, the algorithm may be applied to one region. For these reasons, the algorithm is implemented and applied to the West Anatolia Region since the system data of this region are easily accessible and the boundaries with other regions are comparatively less than the other regions.

As a beginning of the simulation studies, the system model of Turkish grid is constructed by using the system data which are obtained from TEİAŞ. The elements in the West Anatolia Region are kept in the system model, and the rest of Turkish grid is represented as Extended Ward equivalents at the boundary points of the West

Anatolia Region. Network Reduction Tool is used for the Extended Ward equivalents at the boundaries of the West Anatolia Region. This tool is an internal tool implemented in DigSilent. The tool determines the parameters of Extended Ward equivalents at the boundaries such that the load flow results of the reduced model and the full model are equivalent. The Network Reduction Tool implement new elements between the busbars at the boundaries in order to represent the connectivity of the busbars at the boundaries. The boundaries of the West Anatolia Region have been defined for the Network Reduction Tool in DigSilent. The boundaries are shown as red arrows in Figure 5.1.

The size of the West Anatolia Region is larger than the size of the grids of most countries. In the West Anatolia Region, there are 66 power plants with a total installed capacity of 9775 MW. There are 20 busbars whose nominal voltage is 400 kV and 150 busbars whose nominal voltage is 154 kV. There are 24 autotransformers which connect the 400 kV and 154 kV grids. The simulations are performed for heavy load conditions. The peak power demand of the region is 5400 MW for the day which the summer peak has occurred.

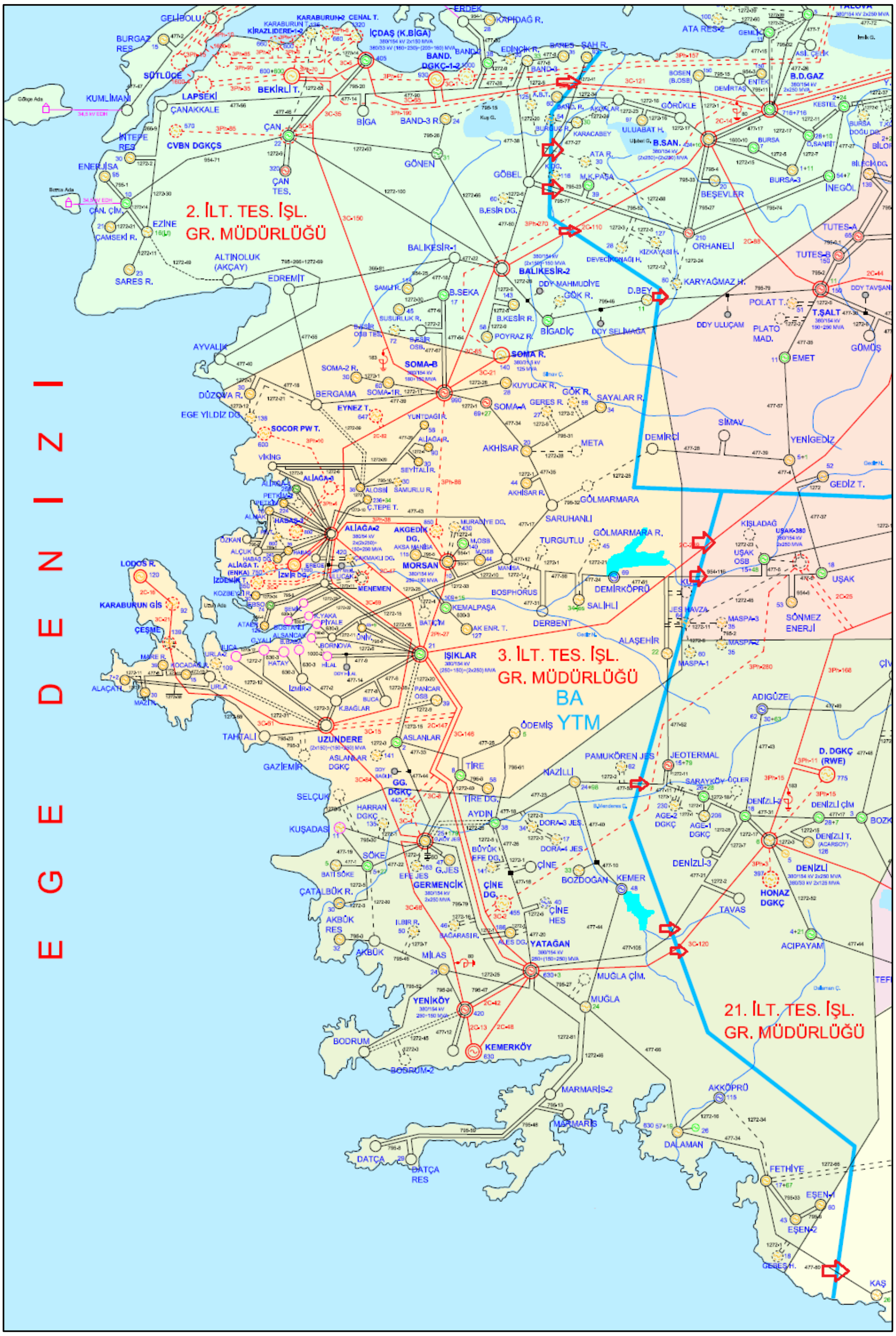

Figure 5.1. Boundaries of West Anatolia Region

Optimal power flow studies for the voltage control issue is conducted with the system data which is obtained from TEİAŞ; however, the system data is not sufficient for this study because of three problems. The first problem is that the active and reactive power demands of the loads are constant in the system model. However in the reality, active and reactive power demands of most of the loads are dependent to the voltage of the busbar which the loads are connected. In order to resolve the first problem, voltage dependency factors of the loads will be modeled. Modeling of the voltage dependency factors has been explained in the previous chapters.

The second problem is the arrangements of the generators. Initially the units are modeled separately. Nevertheless, only one generator can control the voltage of a busbar in the optimal power flow solution in DigSilent. In order to overcome this problem, one generator will be in service while the other generators are out of service and number of generators data will be assigned as the number of parallel machines parameter of the activated generator. As a result, the number of generators will be unaffected and one generator will control the voltage of the generator busbar.

The third problem is the presence of some floating busbars. Some of the network elements are taken out of service as a part of operational actions by the system operator. In addition, the generators and step up transformers may be out of service. In these cases, the network elements are out of service; on the other hand, the busbars that these elements are connected may be in service. This may yield to the presence of floating busbars in the system data. In this case, OPF tool is trying to regulate the voltage of these busbars and this leads to a problem for the OPF tool. To avoid this problem, these floating busbars will be put out of service. Finally, modeling of all system elements will be done and the 400 kV grid will be such as in Figure 5.2.

In the final step before the algorithm is executed, the active power outputs of the power plants and the power demands of the loads will be modeled. The active power dispatch data which are determined in the day ahead market, are obtained from the market operator and the active power outputs of the power plants and the power demands of the loads will be updated accordingly. Additionally, the data of the price offers for 1 MW increase or 1 MW decrease in the output power of the power plants are obtained from the market operator, and these data are used in redispatch optimization studies as well. Since the active power dispatch data and the price offers are commercially confidential, the active power dispatch data are given without the names of the power plants.

Stage I of the algorithm, which is explained in detail in Chapter 4, is simulated using DigSilent. Two operation scenarios have been constituted for the simulation studies. The simulations are conducted for 24 hours for each scenario. For Scenario 1, where the topology of the system is used without any modification, voltage limit violations occur during the first 9 and the last hour of the day. These violations develop in one region. To simulate the case that voltage limit violations occur in two electrically different regions, a 40 MVAr shunt reactor is connected to the system at busbar Kocadağ which is in the west side of the grid. By this way, Scenario 2 is formed and used in simulation studies.

For each hour, the voltage setpoint value assigned for a power plant is assumed to remain constant. Hence, the voltage setpoints for the power plants are determined for each hour. For this reason, the algorithm is executed for each hour separately and the hours are represented by the end time of the hour. In other words, the time from 00:01 to 01:00 is represented as hour 1 and the time between 23:01 and 00:00 of the next day is represented as hour 24.

For Scenario 1, during the hours from hour 09:01 to 23:00, voltage limit violations occur in one region. Likewise, in Scenario 2, there are no voltage limit violations during the first 9 hours and at the last hour of the day. During the rest of the day, voltage limit violations occur in two regions. For the situations that voltage limit violations are occurred, Stage II of the algorithm is executed in order to resolve these violations.

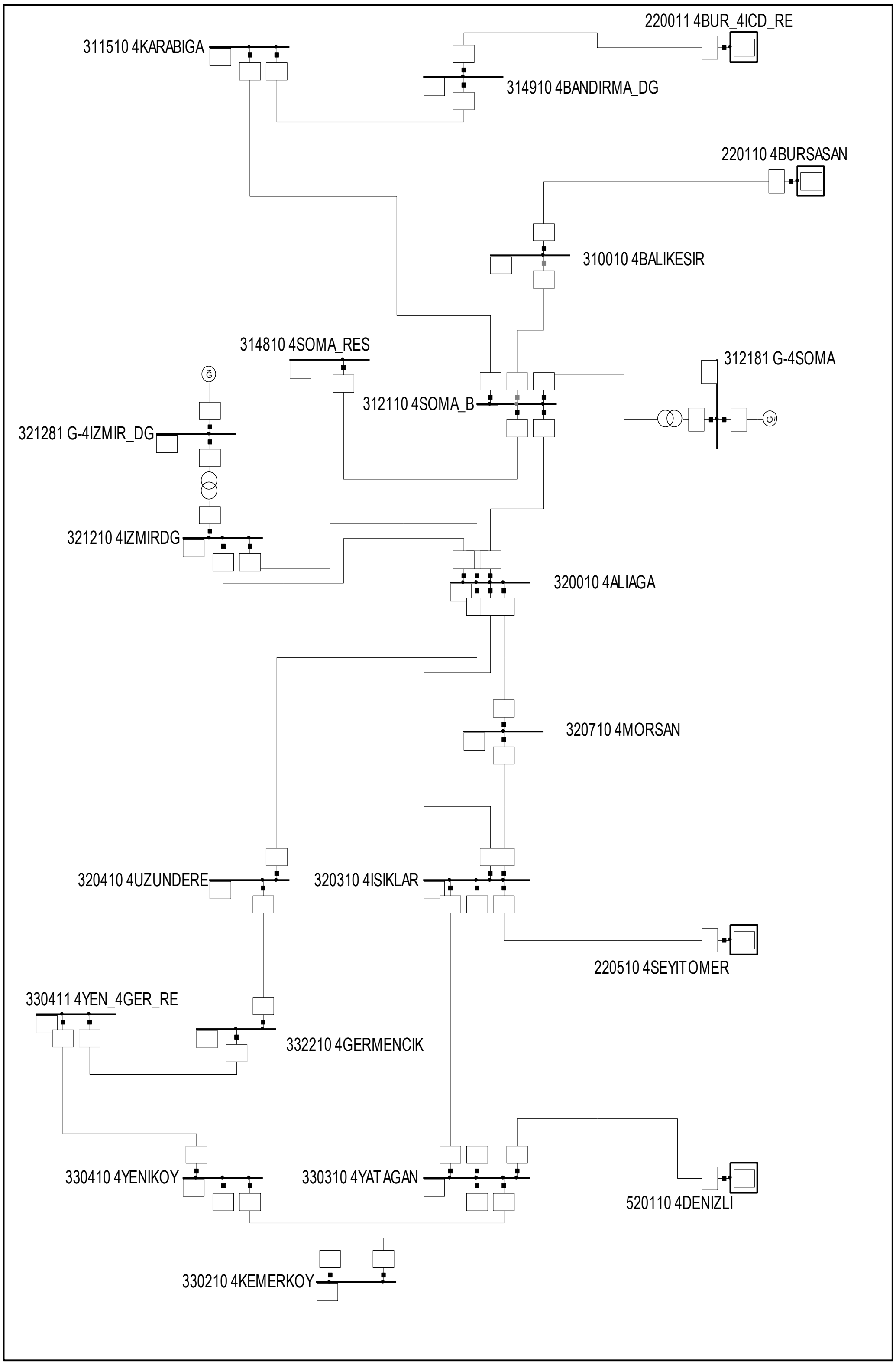

Figure 5.2. Single Line Diagram of West Anatolia Region (400kV Grid)

5.1 Scenario 1 – Low Voltages in One Region

The active power dispatch data are used as an input for the algorithm developed in order to determine the voltage setpoint values of the power plants. During the first nine hours, Stage I of the algorithm optimizes the voltage profile along the system without any violation of the desired limits. The results of the hour 8 will be discussed in order to demonstrate the results of the first 9 hours. The active power dispatch data of the hour 8 is shown in Table 5.1. The names and the locations of the power plants are not given since these data are confidential.

Table 5.1. Active Power Dispatch Data for the Hour 8

Gen Name	Hour 8 (MW)	Gen Name	Hour 8 (MW)	Gen Name	Hour 8 (MW)
PP-1	0	**PP-22**	6	**PP-43**	0
PP-2	4	**PP-23**	0	**PP-44**	2
PP-3	0	**PP-24**	5	**PP-45**	115
PP-4	0	**PP-25**	0	**PP-46**	0
PP-5	294	**PP-26**	0	**PP-47**	80
PP-6	3	**PP-27**	75	**PP-48**	546
PP-7	0	**PP-28**	35	**PP-49**	390
PP-8	404	**PP-29**	0	**PP-50**	355
PP-9	11	**PP-30**	0	**PP-51**	37
PP-10	0	**PP-31**	1339	**PP-52**	0
PP-11	796	**PP-32**	0	**PP-53**	0
PP-12	0	**PP-33**	225	**PP-54**	0
PP-13	0	**PP-34**	0	**PP-55**	0
PP-14	0	**PP-35**	43	**PP-56**	0
PP-15	60	**PP-36**	162	**PP-57**	0
PP-16	57	**PP-37**	0	**PP-58**	0
PP-17	3	**PP-38**	39	**PP-59**	1
PP-18	5	**PP-39**	0	**PP-60**	43
PP-19	1	**PP-40**	101	**PP-61**	0
PP-20	0	**PP-41**	7	**PP-62**	0
PP-21	1	**PP-42**	111		

At the end of the simulation for the hour 8, the optimum voltage profile is reached. The resulting voltage setpoints of the power plants for the hour 8 is shown in Table 5.2. The voltage profile map for the hour 8 in Scenario 1 is shown in Figure 5.3. All of the voltage values are found to be within the desired limits. The busbars which are shown as blue points, are weak busbars since they are electrically distant to the strong busbars. Meanwhile, the reactive power reserves of the power plants which are in service and close to these weak busbars, are not sufficient to increase the voltage values of these weak busbars. In addition, due to the active power demand in those regions, the voltage of these busbars develop near the desired minimum voltage limit, 0.95 pu.

Table 5.2. The Voltage Setpoints of the Power Plants for the Hour 8 – Scenario 1

Gen Name	Hour 8 (kV)	Gen Name	Hour 8 (kV)	Gen Name	Hour 8 (kV)
PP-1	-	**PP-22**	33.262	**PP-43**	-
PP-2	33.067	**PP-23**	-	**PP-44**	33.843
PP-3	-	**PP-24**	34.500	**PP-45**	155.035
PP-4	-	**PP-25**	-	**PP-46**	-
PP-5	156.381	**PP-26**	-	**PP-47**	34.216
PP-6	34.561	**PP-27**	156.201	**PP-48**	393.966
PP-7	-	**PP-28**	34.405	**PP-49**	394.329
PP-8	399.958	**PP-29**	-	**PP-50**	394.251
PP-9	34.105	**PP-30**	-	**PP-51**	157.529
PP-10	-	**PP-31**	391.688	**PP-52**	-
PP-11	402.385	**PP-32**	-	**PP-53**	-
PP-12	-	**PP-33**	155.109	**PP-54**	-
PP-13	-	**PP-34**	-	**PP-55**	-
PP-14	-	**PP-35**	32.749	**PP-56**	-
PP-15	153.859	**PP-36**	34.468	**PP-57**	-
PP-16	154.766	**PP-37**	-	**PP-58**	-
PP-17	22.007	**PP-38**	33.776	**PP-59**	22.000
PP-18	19.883	**PP-39**	-	**PP-60**	159.248
PP-19	22.103	**PP-40**	155.101	**PP-61**	-
PP-20	-	**PP-41**	31.500	**PP-62**	-
PP-21	6.300	**PP-42**	10.858		

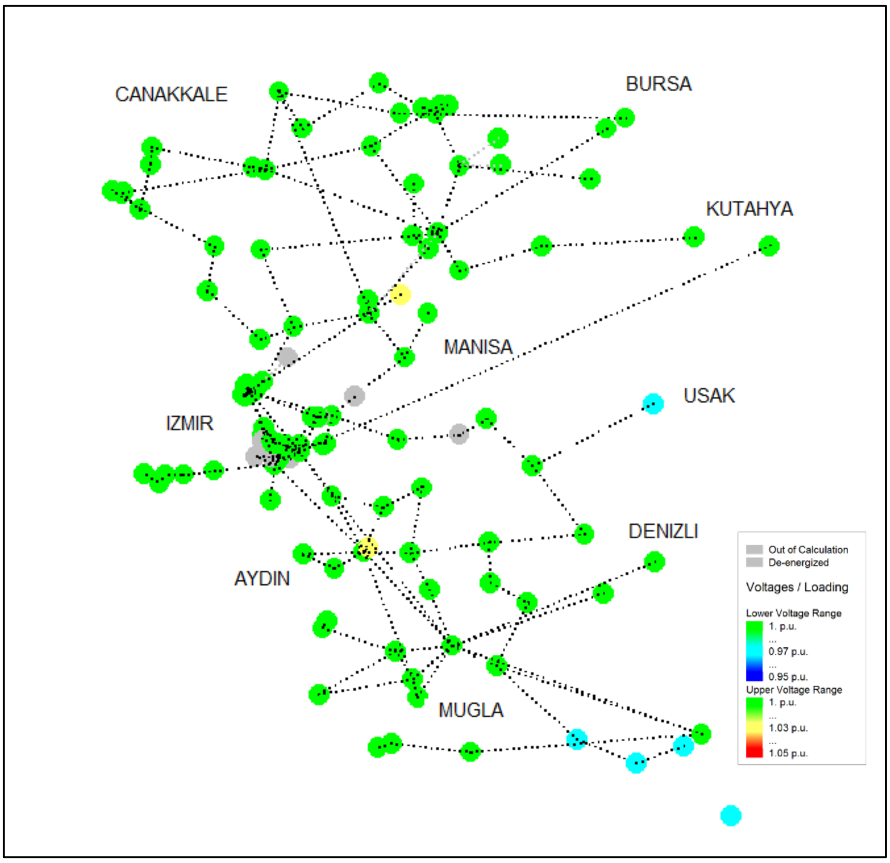

Figure 5.3. Voltage Profile Map for the Hour 8 – Scenario 1

During the time from the hour 10 to the hour 23, voltage limit violations occur on the south side of the grid. At the hour 18, the most severe system condition occurred. The reason of this situation is that the total power demand of the loads are maximum for this hour as can be seen in Table 5.3. The active power dispatch data for the hour 18 is shown in Table 5.4.

Table 5.3. Total Demand for 24 Hours

	Total Demand (MW)		**Total Demand (MW)**
Hour 1	3347	**Hour 13**	4179
Hour 2	3153	**Hour 14**	4292
Hour 3	3034	**Hour 15**	4309
Hour 4	2985	**Hour 16**	4334
Hour 5	2970	**Hour 17**	4544
Hour 6	3000	**Hour 18**	4627
Hour 7	3147	**Hour 19**	4426
Hour 8	3351	**Hour 20**	4279
Hour 9	3895	**Hour 21**	4161
Hour 10	4219	**Hour 22**	4090
Hour 11	4323	**Hour 23**	4128
Hour 12	4396	**Hour 24**	3953

Table 5.4. Active Power Dispatch Data for the Hour 18

Gen Name	**Hour 8 (MW)**	**Gen Name**	**Hour 8 (MW)**	**Gen Name**	**Hour 8 (MW)**
PP-1	0	**PP-22**	1	**PP-43**	0
PP-2	1	**PP-23**	0	**PP-44**	2
PP-3	0	**PP-24**	1	**PP-45**	115
PP-4	0	**PP-25**	0	**PP-46**	3
PP-5	276	**PP-26**	0	**PP-47**	78
PP-6	2	**PP-27**	68	**PP-48**	501
PP-7	0	**PP-28**	34	**PP-49**	410
PP-8	404	**PP-29**	0	**PP-50**	380
PP-9	5	**PP-30**	0	**PP-51**	37
PP-10	0	**PP-31**	1341	**PP-52**	0
PP-11	650	**PP-32**	0	**PP-53**	0
PP-12	0	**PP-33**	224	**PP-54**	0
PP-13	0	**PP-34**	0	**PP-55**	0
PP-14	0	**PP-35**	43	**PP-56**	0
PP-15	54	**PP-36**	165	**PP-57**	0
PP-16	54	**PP-37**	0	**PP-58**	0
PP-17	2	**PP-38**	38	**PP-59**	0
PP-18	7	**PP-39**	0	**PP-60**	43
PP-19	4	**PP-40**	93	**PP-61**	4
PP-20	4	**PP-41**	2	**PP-62**	0
PP-21	1	**PP-42**	106		

Figure 5.4. South Side of West Anatolia Grid

At the hour 18, the voltages of the 154 kV busbars of the Fethiye, Esen and Dalaman substations are below the desired minimum voltage limit, 0.95 pu. The southern part of the grid is found to be weak since there are not sufficient reactive power reserves to support the voltages along the southern part of the grid. Another reason of the weak busbars is the electrical distance of these busbars to the 400 kV grid. As shown in Figure 5.4, the 154 kV grid is extended to Fethiye; even though, the 400 kV grid is finished at Kemerköy. For this reason, the voltages are resulted below the desired minimum voltage limit in the south region where only the 154 kV grid is present.

The simulation results for the hour 18 reveal that there are voltage limit violations at the 154 kV busbars of the Fethiye, Esen and Dalaman substations around Fethiye and Dalaman region as shown in Figure 5.5. The voltages of these busbars are below the desired minimum voltage limit, 0.95 pu, with the minimum of them is 0.89 pu (136.9 kV). In this case, the current reactive power reserves of the grid elements are not sufficient to maintain these voltages within the desired limits. In the voltage profile optimization problem, the OPF tool is used to optimize the voltage profile. In the OPF solution, the switchable shunt reactors and tap positions of the transformers are used for the optimization of the voltage profile. Hence, the only solution to keep the voltages within the limits is getting additional reactive power from the power plants. It is performed by redispatching the power plants. For that purpose, Stage II of the algorithm, which is developed using Matlab for the minimization of the cost of corrective actions, is executed.

In Stage II of the algorithm, the effects of the change in the active power outputs of the power plants on the busbars, whose voltages are out of the desired limits, are represented in the constraints of the optimization problem. Hence, the voltage sensitivity factors of the generators on the problematic busbars are calculated using DigSilent and exported as text files. These text files are imported to the Matlab and used in Stage II of the algorithm. Besides the data calculated using DigSilent, the data of price offers for 1 MW increase and decrease in the active power output are used in Stage II of the algorithm in Matlab.

As explained in the previous chapters, in the first iteration of Stage II in Matlab, it is assumed that the problematic busbars are electrically close to each other. As shown in Figure 5.5, the 154 kV busbars of the Fethiye, Esen and Dalaman substations, whose voltages are below the desired minimum voltage limit are electrically close. Hence, the busbar with the minimum voltage value is selected for the calculation of $dVbus/dP_i$ factors which are included in the constraints of the optimization problem in Stage II of the algorithm. The resulted redispatch data are exported to an excel sheet to be used for the voltage profile optimization in DigSilent.

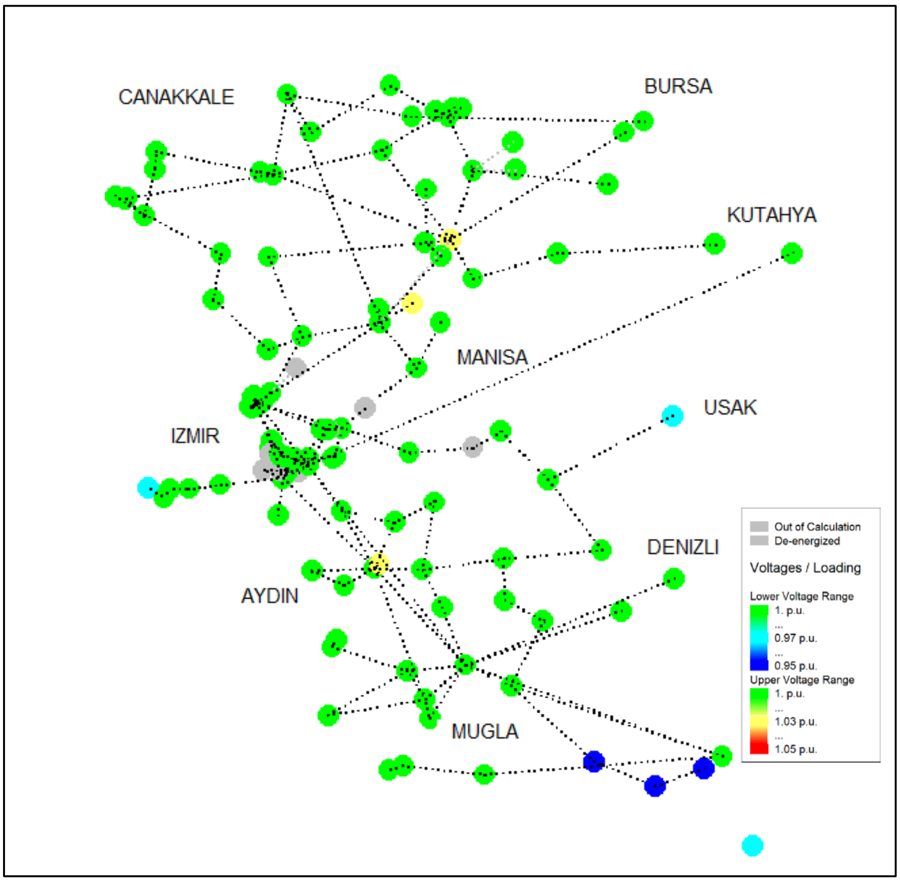

Figure 5.5. Voltage Profile Map for the Hour 18 – Scenario 1

According to the results of the redispatch optimization, there are changes in the active power outputs of the seven power plants. The geographic locations of these power plants are shown in Figure 5.6 and the amount of the changes in the active power output levels of these power plants are shown in Table 5.5. As the result of the redispatch of these power plants, the voltage limit violations at the 154 kV busbars of the Fethiye, Esen and Dalaman substations are resolved. Active power output of the power plant PP-50 is decreased in order to increase the reactive power capability. The power plant PP-52 is taken into service. The redispatch optimization solves the problem so that the sum of the changes in the active power outputs of all the power plants must be zero. Hence, the remaining five power plants are redispatched so that the sum of changes in the active power outputs is zero.

Table 5.5. Redispatch Results for the Hour 18 – Scenario 1

	PP-5	PP-9	PP-37	PP-39	PP-41	PP-50	PP-52
Initial Active Power Output Level (MW)	276	5	0	0	2	380	0
Final Active Power Output Level (MW)	299	28	28	16	36	238	19

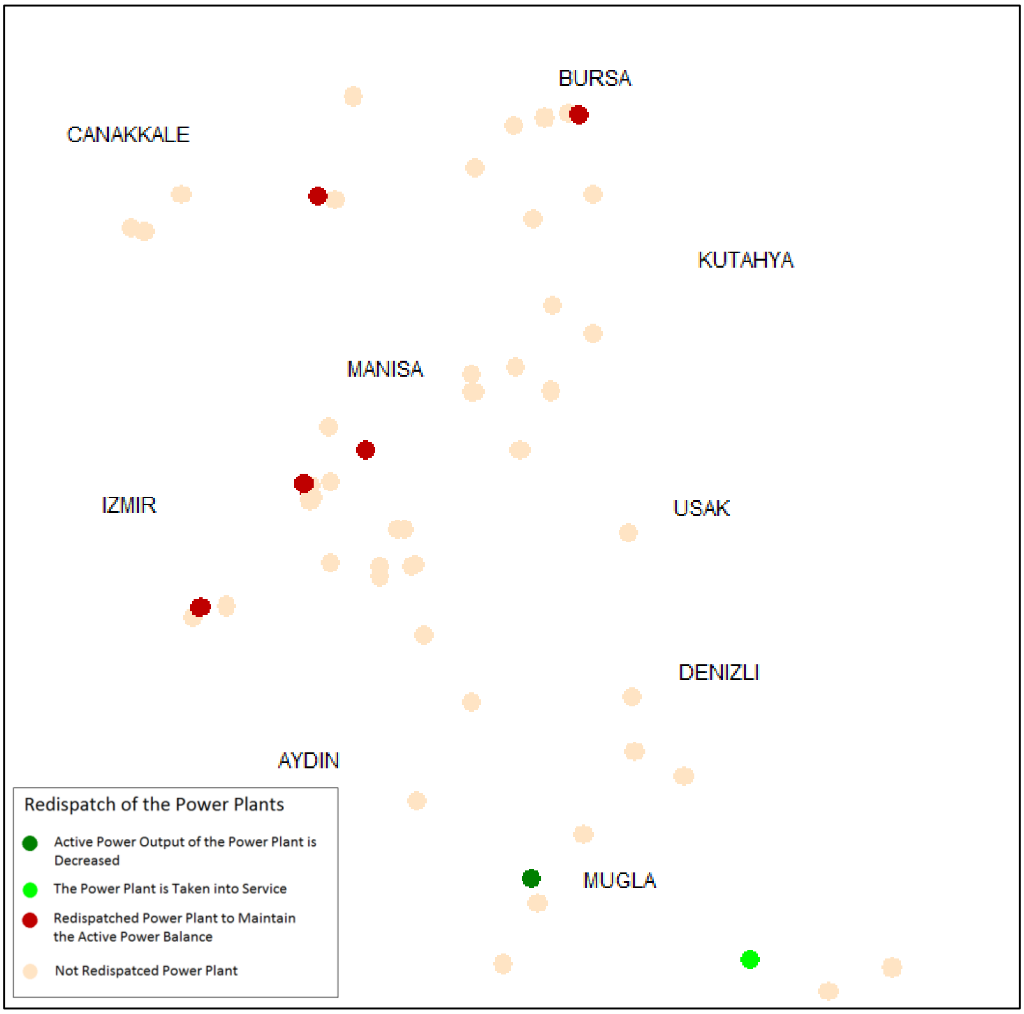

Figure 5.6. Redispatched Power Plants for the Hour 18 – Scenario 1

The results of Stage II are imported to the DigSilent. Stage I of the algorithm is executed again with the updated active power dispatch data in order to confirm that the optimum voltage profile is ensured without any voltage limit violation. The results of Stage I with the updated active power dispatch data show that voltages of all of the busbars concerned are found within the limits. The resulting voltage values of the busbars before and after the corrections are shown in Table 5.6. The final voltage profile map for hour 18 is shown in Figure 5.7. The resulting voltage setpoints of the power plants for the hour 18 is shown in Table 5.7.

According to the results of Stage II in Matlab, it can be concluded that the power plants PP-50 and PP-52 are redispatched in order to resolve the voltage limit violations at the 154 kV busbars of the Fethiye, Esen and Dalaman substations whose voltages are below the desired minimum voltage limit. The other power plants are redispatched to ensure the power balance in the grid. As can be seen in Figure 5.7, the remaining power plants are electrically far from the problematic busbars. The effects of these power plants are insignificant, the reason of the redispatch of these power plants is that the costs of these power plants are optimum. The cost of redispatch of these power plants are cheaper than the other power plants.

Table 5.6. The Voltages of the Busbars whose Voltages are out of Limits for the Hour 18 – Scenario 1

	Before the Corrections	After the Corrections
Fethiye (kV)	136.94	146.39
Esen (kV)	137.02	146.48
Dalaman (kV)	140.35	149.41

Table 5.7. The Voltage Setpoints of the Power Plants for the Hour 18 – Scenario 1

Gen Name	Hour 18 (kV)	Gen Name	Hour18 (kV)	Gen Name	Hour 18 (kV)
PP-1	-	**PP-22**	33.368	**PP-43**	-
PP-2	31.714	**PP-23**	-	**PP-44**	34.050
PP-3	-	**PP-24**	34.500	**PP-45**	156.667
PP-4	-	**PP-25**	-	**PP-46**	31.250
PP-5	156.378	**PP-26**	-	**PP-47**	34.573
PP-6	34.331	**PP-27**	158.393	**PP-48**	404.143
PP-7	-	**PP-28**	34.559	**PP-49**	403.928
PP-8	403.397	**PP-29**	-	**PP-50**	404.377
PP-9	34.557	**PP-30**	-	**PP-51**	160.135
PP-10	-	**PP-31**	402.640	**PP-52**	6.4
PP-11	407.540	**PP-32**	-	**PP-53**	-
PP-12	-	**PP-33**	156.879	**PP-54**	-
PP-13	-	**PP-34**	-	**PP-55**	-
PP-14	-	**PP-35**	32.576	**PP-56**	-
PP-15	155.287	**PP-36**	34.707	**PP-57**	-
PP-16	154.084	**PP-37**	157.49	**PP-58**	-
PP-17	21.958	**PP-38**	34.039	**PP-59**	-
PP-18	19.851	**PP-39**	152.04	**PP-60**	161.304
PP-19	22.180	**PP-40**	156.814	**PP-61**	34.734
PP-20	22.118	**PP-41**	31.500	**PP-62**	-
PP-21	6.300	**PP-42**	11.116		

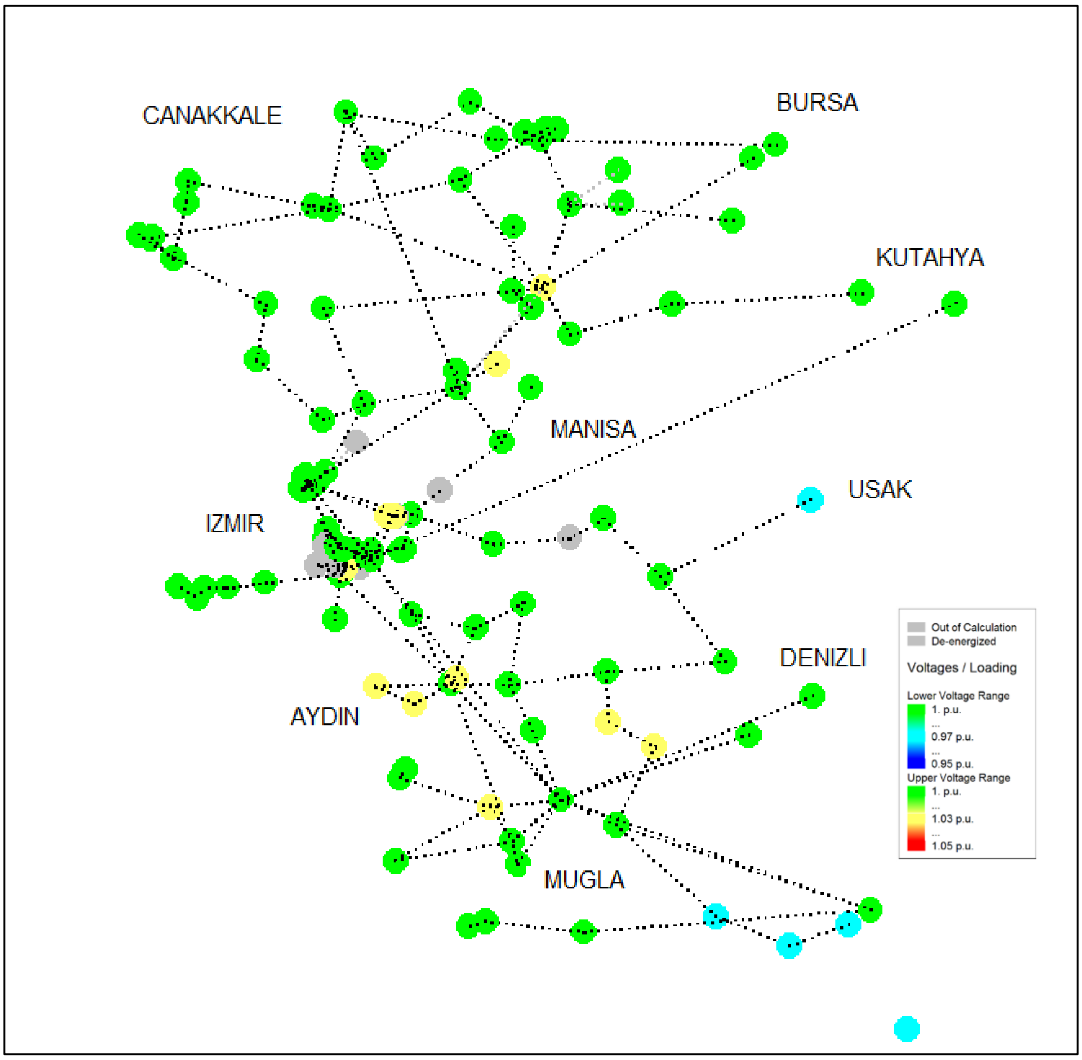

Figure 5.7. Final Voltage Profile Map for the Hour 18 – Scenario 1

5.2 Scenario 2 – Low Voltages in Two Regions

In Scenario 1, voltage limit violations occurred in one region and Stage II solves the problem in one iteration. To verify the algorithm completely, the case that voltage limit violations occurred in more than one region should be simulated. Hence, a 40 MVAr shunt reactor is connected to the Kocadağ 154 kV busbar whose voltage is minimum and electrically far from the Fethiye and Dalaman region. The place of the shunt reactor is shown in Figure 5.8.

Figure 5.8. The Place of the Shunt Reactor

In Scenario 2, Stage I of the algorithm finds a feasible optimum solution for the voltage setpoints of the power plants successfully for the first eight hours. In other words, no voltage limit violations occurred in the first eight hours. Due to the shunt reactor connected Kocadağ 154 kV busbar, the voltages of the busbars near Kocadağ are very close to the desired minimum voltage limit. The voltage profile map is shown in Figure 5.9.

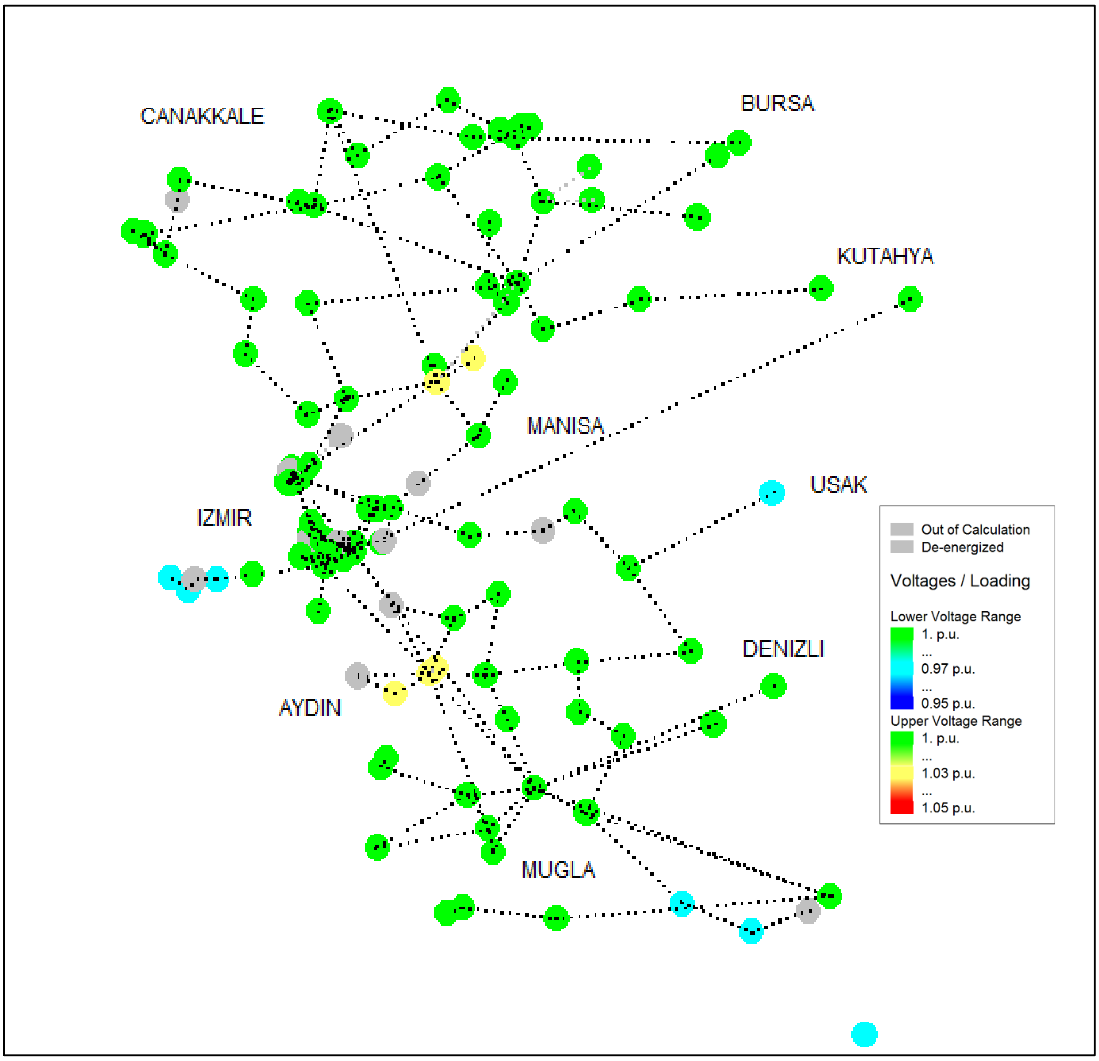

Figure 5.9. Voltage Profile Map for the Hour 8 – Scenario 2

Similar to Scenario 1, voltage limit violations occur during the time from hour 10 to hour 23. The effects of the shunt reactor are most severe at the hour 18 in Scenario 2 since the heaviest load conditions occur in this hour. Therefore, the results of Scenario 2 for the hour 18 will be discussed in order to show the validity of the overall algorithm. In the hour 18, voltage limit violations occurred in two electrically far regions. One of them is around Fethiye and Dalaman as in Scenario 1, and the second one is around Kocadağ in the west side of the West Anatolia Region as shown in Figure 5.10.

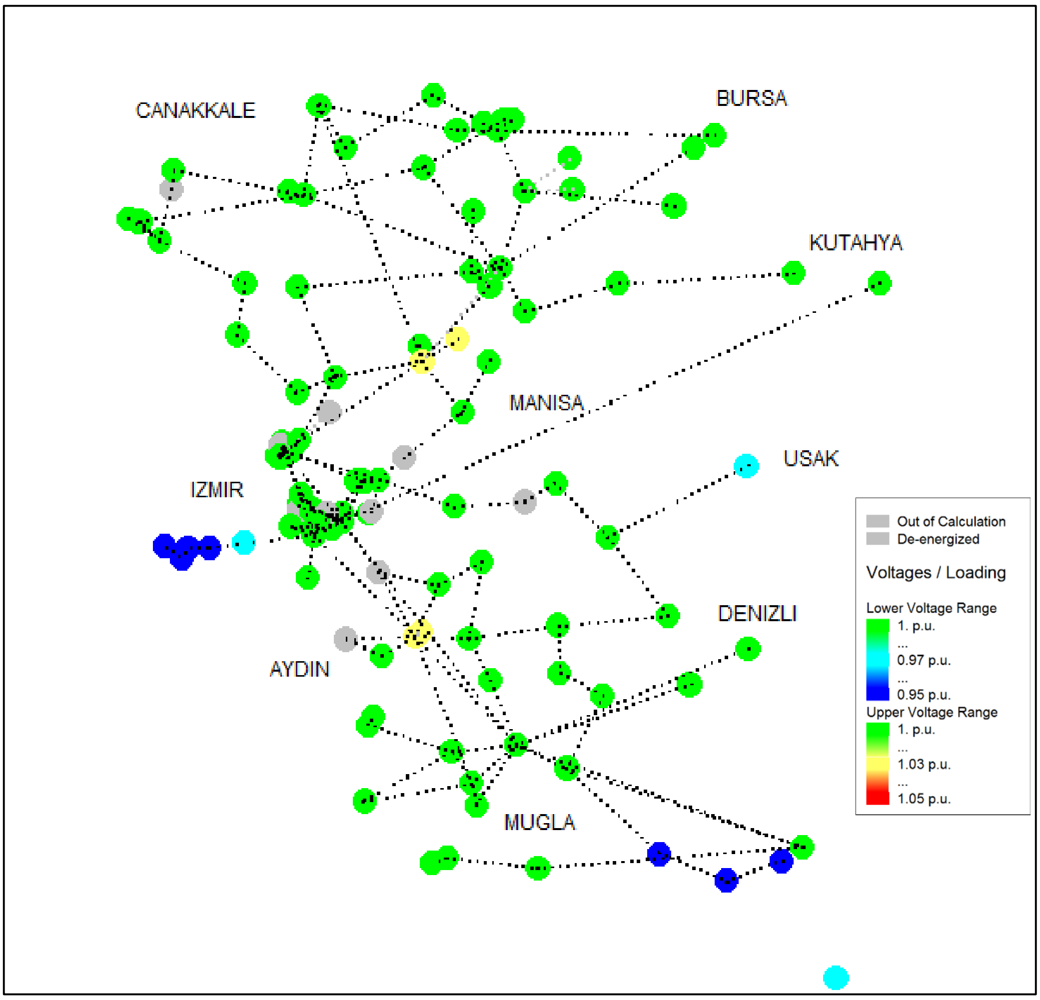

Figure 5.10. Voltage Profile Map for the Hour 18 – Scenario 2

In this scenario, 7 busbars with voltages below the minimum voltage limit occurred in two electrically far regions. The voltage sensitivity data are exported from DigSilent and imported into Matlab to be used in Stage II. In the first iteration of Stage II, it is assumed that problematic busbars are electrically close to each other, so the voltage sensitivities of the generators to the busbar with the minimum voltage are added into the set of constraints and Stage II is executed.

The redispatch results after the first iteration of Stage II are the same as the results in Scenario 1 since the busbar considered in the constraints is the same busbar as in

Scenario 1. The resulting redispatch data are imported to the DigSilent and Stage I is executed to check if there any voltage limit violations occur. The resulting voltage profile map is presented in Figure 5.11.

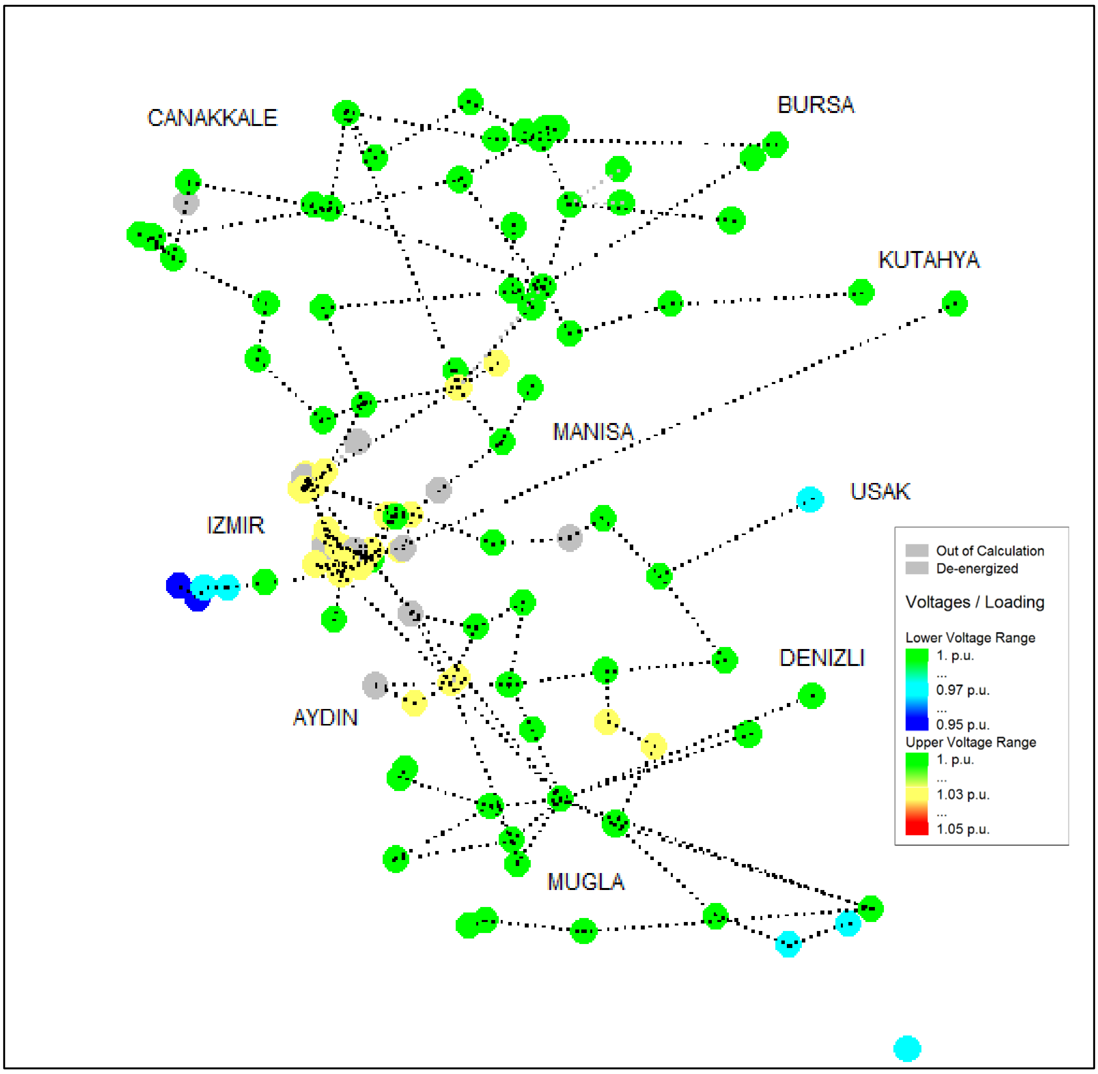

Figure 5.11. Voltage Profile Map for Hour 18 – Scenario 2

As shown in Figure 5.11, with the assumption that the voltage limit violations occurred in a region, the problem can not be solved in Stage II when this is not the case. In order to solve the problem, Stage II is executed again. But this time, it is assumed that the voltage limit violations occurred in two regions as in Scenario 2. For that purpose, two busbars are selected so that these two busbars will be electrically furthest along all seven busbars whose voltages are below the desired minimum voltage limit.

In order to find the electrically furthest busbars, the voltage sensitivity factors between the busbars are used. The voltage sensitivity factors are calculated in DigSilent. When two busbars are electrically far from each other, the magnitude of the voltage sensitivity factor will be smaller. By using this fact, the two busbars are selected such that the voltage sensitivity factor between these two busbars is the minimum. After the selection of these two busbars, the effects of the power plants to these two busbars are added into the set of constraints in Stage II. Stage II is executed again and the results of Stage II are imported to the DigSilent in order to check that if there is still any voltage limit violation. The resulting redispatch data are shown in Figure 5.12. The amount of the changes in the active power output levels of these power plants are shown in Table 5.8.

Table 5.8. Redispatch Results for the Hour 18 – Scenario 2

	PP-5	**PP-9**	**PP-12**	**PP-23**	**PP-31**	**PP-37**	**PP-39**	**PP-41**	**PP-52**
Initial Active Power Output Level (MW)	276	5	0	0	1341	0	0	2	0
Final Active Power Output Level (MW)	467	28	78	432	521	28	16	36	19

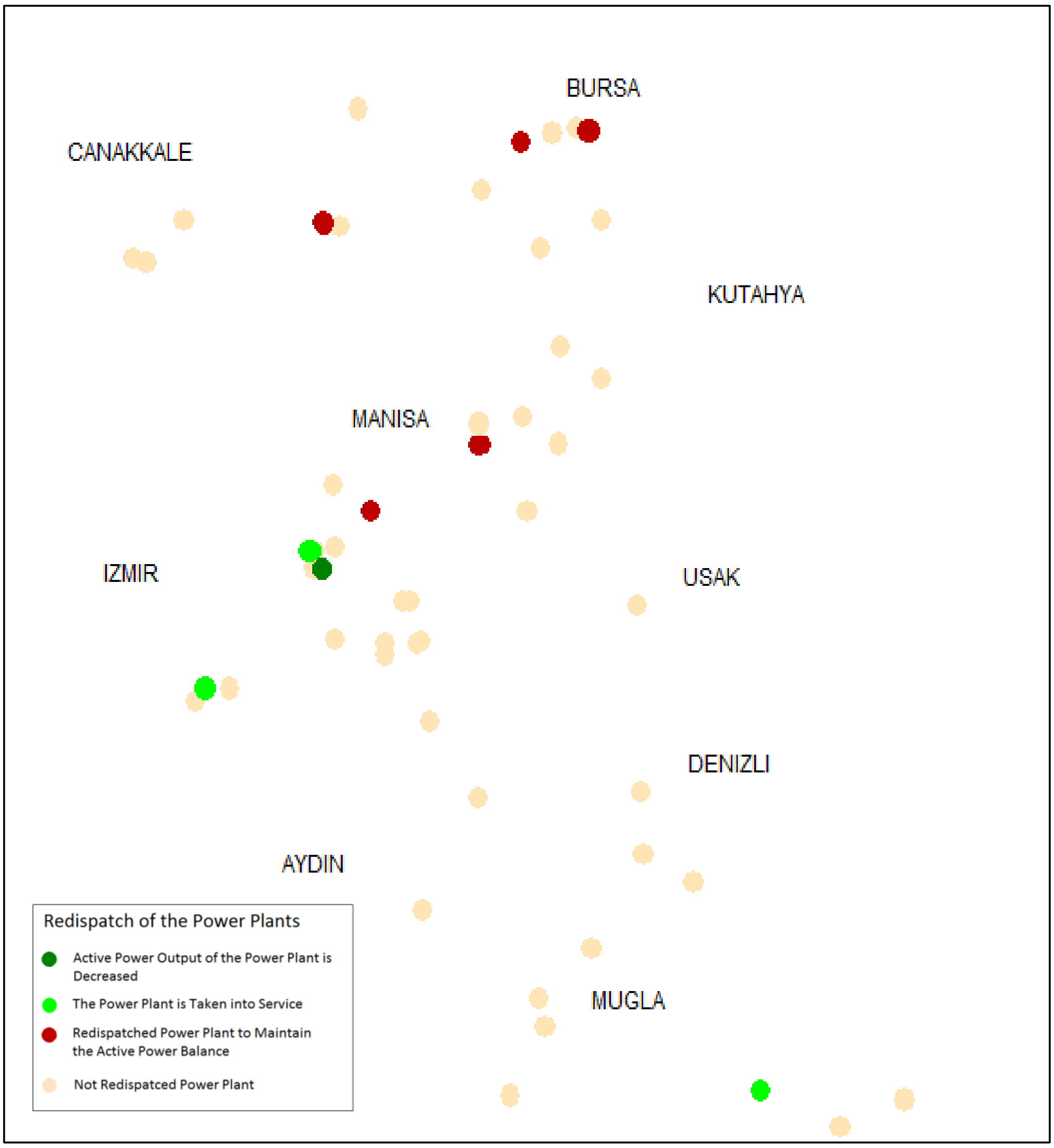

Figure 5.12. Redispatched Power Plants for Hour 18 – Scenario 2

As the result of the second iteration of Stage II, nine power plants are redispatched. The active power output of the power plant PP-31 is decreased in order to increase its reactive power capability. In addition, the power plants PP-37, PP-39 and PP-52 are taken into service for their reactive power capabilities. In order to maintain the active power balance in the system, the rest of the power plants, which are presented in Figure 5.12 and Table 5.8, are redispatched. As can be seen in Figure 5.12, the power plants PP-31, PP-37, PP-39 are electrically close the Kocadağ region whereas the power plant PP-52 is electrically close to Fethiye – Dalaman region.

The redispatch data resulted from the second iteration of Stage II are imported to the DigSilent to check whether an optimum feasible solution is reached with the updated active power dispatch data. As the result of Stage I, the optimum voltage profile has been reached with the desired voltage limits. The voltages of the busbars which are initially out of the desired voltage limits are corrected. The change in the voltages of these busbars are presented in Table 5.9, and the resulting voltage profile map is illustrated in Figure 5.13.

Table 5.9. The Voltages of the Busbars whose Voltages are out of Limits for the Hour 18 – Scenario 2

	Before the Corrections	**After the 1st iteration of Stage II**	**After the 2nd iteration of Stage II**
Fethiye (kV)	137.38	146.4	146.36
Esen (kV)	137.46	146.5	146.45
Dalaman (kV)	140.77	149.4	149.4
Alaçatı (kV)	142.20	144.7	146.3
Mazı (kV)	143.14	145.6	147.2
Mare (kV)	144.04	146.5	148.1
Kocadağ (kV)	145.96	147.3	148.85

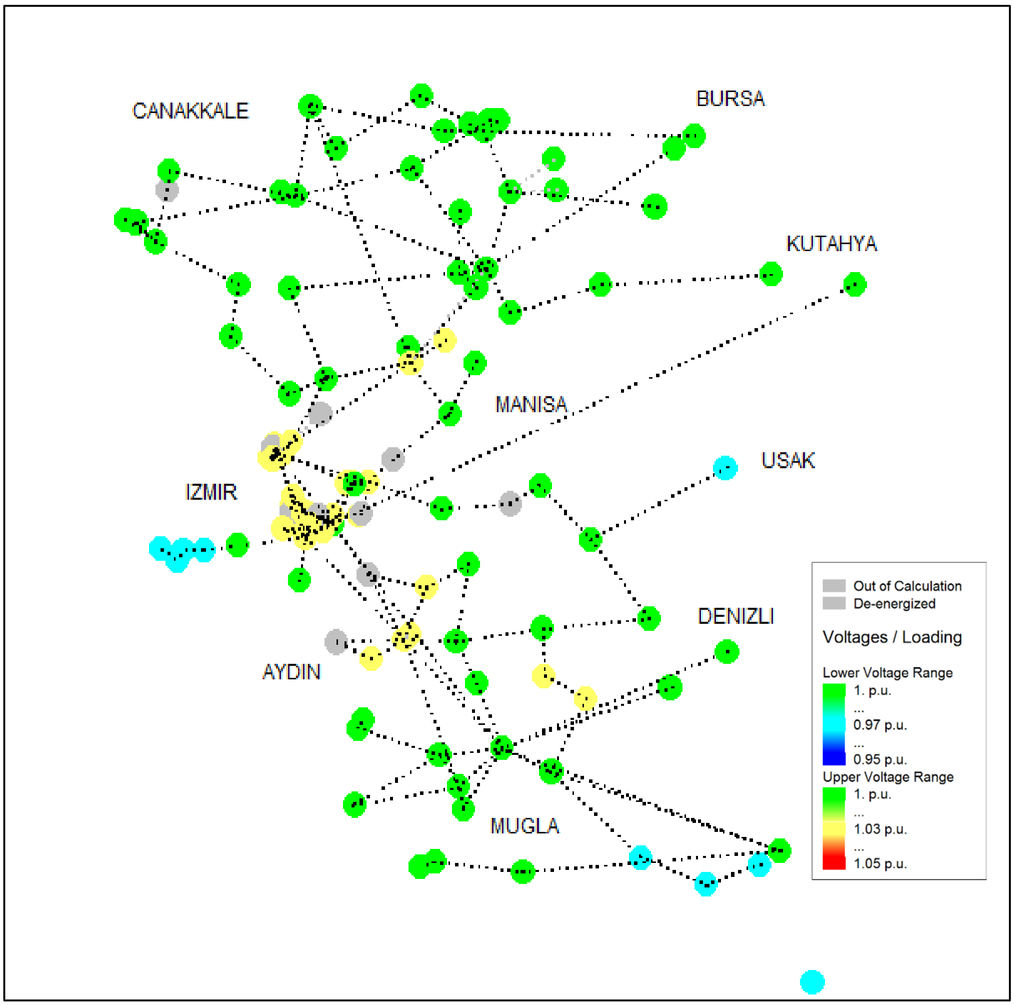

Figure 5.13. Final Voltage Profile Map for Hour 18 – Scenario 2

The results of the simulations show that the overall algorithm which consists of two stages solves the problem that is investigated in this thesis study. When the load conditions are not heavy, the voltage setpoints for HV busbars of the power plants can be determined by Stage I of the algorithm developed in DigSilent. As the load conditions get heavier, Stage I can not handle the issue. At this point, the need for the optimization of the redispatch of the power plants comes into the picture and the voltage setpoints can be determined by the help of Stage II. As a result, the simulations show that the overall algorithm is able to determine the voltage setpoints for HV busbars of the power plants.

CHAPTER 6

CONCLUSION

Voltage control and frequency control are the basic categories under the ancillary services which are required for the quality of service in a modern power system. Frequency control can be divided into three hierarchical levels; primary, secondary and tertiary frequency control. The aim of the frequency control is to maintain the frequency at an acceptable level by controlling the active power outputs of the generators. Likewise, voltage control can be divided into three hierarchical levels. The aim of the voltage control is to maintain the voltages at an acceptable level by controlling the reactive power outputs of the generators.

Since December 2011, there is a day ahead market operating in Turkey. Active power dispatch on an hourly basis for the next day is being set through this market environment and the resulting dispatch is sent to National Load Dispatch Center. Firstly, the active power dispatch is determined based only on the price offers of the power plants. According to the initial active power dispatch, contingency analysis is conducted and security of the system is checked. Based on the results of the contingency analysis, the active power dispatch is updated. The final active power dispatch is sent to National Load Dispatch Center.

After the determination of the active power dispatch, the voltage setpoint values for the HV busbars of the power plants will be determined by the operators in National and Regional Load Dispatch Centers. The determination of these voltage setpoints, which is categorized as tertiary voltage control, is an important part of voltage control. The performance of tertiary voltage control affects the voltage profile along the grid and the transmission losses. Primary and secondary voltage control, which are performed by the power plants, are the regulation of voltage of the generator terminal and HV busbar of the power plant according to the pre-determined setpoints. Hence, the determination of these setpoints is the main part of voltage control that affects the voltage profile along the grid. In addition, the voltage setpoints for the power plants should be determined such that the reactive power flows do not exceed the requirements of the system.

Based on their knowledge and experience about system operating conditions and network connections, operators specify the voltage setpoints for the power plants. Obviously, in this decision process, they do not employ any systematic or analytical approach. Since the reactive power flows are related with the voltage setpoints, transmission losses may be increased due to extra reactive power flows in the system. Hence, the transmission losses should be minimized considering the economic impact.

The goal of this study is to develop a systematic approach which, as a tool, guides and aids the system operators to specify the voltage setpoints for the power plants on an hourly basis for the following day. For this purpose, an algorithm has been developed for the determination of the voltage setpoint values for the high voltage busbars of the power plants. The algorithm has two stages. Stage I is the main part of the algorithm which determines the voltage setpoint values for the high voltage busbars of the power plants. Stage II is the supporting stage of the algorithm. In Stage II, minimization problem for the cost of corrective actions are solved to resolve the voltage limit violations if any.

The system model of the West Anatolia Region is used for the simulations. The rest of the Turkish grid is represented by the Extended Ward equivalents, parameters of which are determined by the network reduction tool in DigSilent. Stage I of the algorithm is developed and simulated in DigSilent, and Stage II of the algorithm is developed and simulated in Matlab.

Two scenarios for the simulation studies are formed in order to verify if the algorithm is successfully operating. Scenario 1 is based on the system model of West Anatolia Region for the day which the summer peak demand occurred and the related data have been obtained from TEİAŞ. In Scenario 1, voltage limit violations occurred at the busbars which are electrically close to each other. In order to simulate a case where voltage limit violations occurred in electrically far regions, Scenario 2 is formed by connecting a shunt reactor at Kocadağ 154 kV busbar.

In each scenario, for some of the hours of the day, the voltage setpoints for the power plants are determined by Stage I of the algorithm. For these hours, no voltage limit violations occurred; hence, Stage II is not executed. On the other hand, for the remaining hours, voltage limit violations occurred in the end of Stage I of the algorithm. Hence, Stage II is executed to resolve these voltage limit violations. In Scenario 1, voltage limit violations occurred in the busbars which are electrically close to each other. Therefore, Stage II successfully resolves the voltage limit violations in one iteration. However, in Scenario 2, voltage limit violations occurred in two different regions; consequently, Stage II of the algorithm resolves the voltage limit violations in two iterations.

As a conclusion, the algorithm developed in this thesis study offers a systematic approach for tertiary voltage control in Turkish power system. The simulation results confirm that the algorithm successfully operates and determines the voltage setpoint values for the high voltage busbars of the power plants. Generally speaking, for light load conditions, Stage I of the algorithm alone determines the voltage setpoints for the power plants. Contrarily, for heavy load conditions, Stage I and II together determines the voltage setpoints for the power plants.

The application of secondary voltage control in some countries differs from the present application in Turkey. In secondary voltage control application of these countries, the grid is split to regions, and the secondary voltage control is performed within these regions. For each region, an automatic regional voltage controller controls the voltage setpoints of the generators within the region in order to regulate the voltage at the pilot node of the region. Design and implementation of the regional controllers, determination of the voltage control regions and the pilot nodes for these regions are the challenges for future work.

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APPENDIX – A

OPTIMAL POWER FLOW PROBLEM

Consider an economic dispatch problem that has an objective function which is the minimization of the total generation costs. Meanwhile the sum of the total system load and the losses must be equal to the total generated power. In addition, active power outputs of the generators must be between the minimum and maximum active power limits. Therefore, the economic dispatch problem will be as in equation A.1.

$$\min f(P) = F_1(P_1) + F_2(P_2) + \cdots + F_N(P_N)$$

such that, (A.1)

$$\sum_{i=1}^{N} P_i - P_{load} - P_{loss} = 0$$

$$P_i^- \leq P_i \leq P_i^+$$

$$i = 1, 2, \ldots, N$$

F_i : Cost Function generator *i*

P_i : Active Power Output of Generator *i*

P_i^- : Minimum Active Power Output of Generator *i*

P_i^+ : Maximum Active Power Output of Generator *i*

P_{load} : Total System Load

P_{loss} : Total Active Power Losses

If we add power flow equations to this economic dispatch problem as constraints, the solution of this optimization problem will be a minimum cost solution that satisfies power flow equations as well. This formulation is named as the Optimal Power Flow problem [12].

The objective function can also take different forms such as minimization of electrical losses, minimization of costs or minimization of load shedding. In any case, power flow equations must be present as constraints in the OPF problem. In addition to the power flow equations, we can consider more power system limits as constraints. Some of these limits are generation reactive power limits, voltage magnitude limits at busbars or power flow limits of branches (lines, transformers, etc.). In addition, control variables vary according to the form of the objective function. Some of these control variables are generator reactive power dispatch or generator voltage setpoint values, transformer tap positions and switchable shunt reactors or capacitors [12], [13].

As a conclusion, different problems can be solved with the help of the OPF calculations by defining the proper objective function. Some of these problems are:

1. The calculation of the optimum generation dispatch that satisfies power flow equations and power system limits.

2. The optimum setpoint values for generator voltages or reactive power outputs, transformer tap positions and switchable shunt reactors or capacitors.

APPENDIX – B

ACTIVE POWER DISPATCH DATA

Table B.1. Active Power Dispatch Data in MW from Hour 1 to Hour 6

Gen Name	Hour_1	Hour_2	Hour_3	Hour_4	Hour_5	Hour_6
PS-1	0	0	0	0	0	0
PS-2	4	4	4	5	2	5
PS-3	0	0	0	0	0	0
PS-4	0	0	0	0	0	0
PS-5	290	290	292	292	293	292
PS-6	1	1	1	1	2	2
PS-7	0	0	0	0	0	0
PS-8	403	403	404	404	404	403
PS-9	10	10	10	10	10	15
PS-10	0	0	0	0	0	0
PS-11	788	780	781	781	786	791
PS-12	0	0	0	0	0	0
PS-13	0	0	0	0	0	0
PS-14	0	0	0	0	0	0
PS-15	60	60	60	60	60	61
PS-16	57	57	57	57	57	57
PS-17	0	0	2	1	0	2
PS-18	6	2	6	7	8	7
PS-19	0	1	1	2	2	1
PS-20	0	0	0	0	3	3
PS-21	0	0	0	0	0	0
PS-22	1	1	1	1	2	3
PS-23	0	0	0	0	0	0
PS-24	4	5	6	6	7	7

Table B.1. (continued)

Gen Name	Hour_1	Hour_2	Hour_3	Hour_4	Hour_5	Hour_6
PS-25	0	0	0	0	0	0
PS-26	0	0	0	0	0	0
PS-27	73	73	73	73	73	66
PS-28	34	34	34	35	35	34
PS-29	0	0	0	0	0	0
PS-30	0	0	0	0	0	0
PS-31	1064	1324	1351	1363	1329	1364
PS-32	0	0	0	0	0	0
PS-33	224	224	224	224	224	224
PS-34	0	0	0	0	0	0
PS-35	43	43	43	43	43	43
PS-36	129	132	133	134	132	135
PS-37	0	0	0	0	0	0
PS-38	39	39	39	39	39	39
PS-39	6	9	10	6	7	4
PS-40	99	100	100	101	102	102
PS-41	0	0	0	0	0	3
PS-42	109	110	113	109	111	111
PS-43	0	8	7	4	2	0
PS-44	7	3	0	0	0	3
PS-45	117	117	118	88	85	85
PS-46	2	6	5	6	0	0
PS-47	80	80	80	80	80	80
PS-48	504	507	504	498	510	543
PS-49	385	390	395	395	400	320
PS-50	295	350	350	360	355	355
PS-51	37	37	37	37	37	37
PS-52	0	0	0	0	0	0
PS-53	0	0	0	0	0	0
PS-54	0	0	0	0	0	0
PS-55	0	0	0	0	0	0
PS-56	0	0	0	0	0	0
PS-57	0	0	0	0	0	0
PS-58	0	0	0	0	0	0
PS-59	0	0	0	1	1	3
PS-60	43	43	44	44	44	44
PS-61	0	0	0	0	0	0
PS-62	0	0	0	0	0	0

Table B.2. Active Power Dispatch Data in MW from Hour 7 to Hour 12

Gen Name	Hour_7	Hour_8	Hour_9	Hour_10	Hour_11	Hour_12
PS-1	0	0	0	0	0	0
PS-2	4	4	5	5	4	5
PS-3	0	0	0	0	0	0
PS-4	0	0	0	0	0	0
PS-5	292	294	296	289	287	283
PS-6	3	3	6	1	2	4
PS-7	0	0	0	0	0	0
PS-8	404	404	405	404	405	404
PS-9	11	11	16	19	15	14
PS-10	0	0	0	0	0	0
PS-11	791	796	791	773	778	697
PS-12	0	0	0	0	0	0
PS-13	0	0	0	0	0	0
PS-14	0	0	0	0	0	0
PS-15	62	60	60	60	57	55
PS-16	57	57	56	56	55	55
PS-17	1	3	3	7	4	2
PS-18	7	5	10	18	8	16
PS-19	2	1	5	5	5	5
PS-20	2	0	1	2	3	4
PS-21	0	1	1	0	0	0
PS-22	5	6	3	3	6	11
PS-23	0	0	0	0	0	0
PS-24	7	5	7	5	8	1
PS-25	0	0	0	0	0	0
PS-26	0	0	0	0	0	0
PS-27	66	75	74	74	73	71
PS-28	34	35	34	35	34	34
PS-29	0	0	0	0	0	0
PS-30	0	0	0	0	0	0
PS-31	1313	1339	1349	1353	1357	1353
PS-32	0	0	0	0	0	0
PS-33	224	225	224	224	224	224
PS-34	0	0	0	0	0	0
PS-35	43	43	43	43	43	43
PS-36	158	162	168	170	172	169
PS-37	0	0	0	0	0	0
PS-38	39	39	39	39	39	39

Table B.2. (continued)

Gen Name	**Hour_7**	**Hour_8**	**Hour_9**	**Hour_10**	**Hour_11**	**Hour_12**
PS-39	1	0	0	0	0	1
PS-40	101	101	102	100	101	98
PS-41	7	7	15	0	0	1
PS-42	111	111	110	110	111	110
PS-43	0	0	0	0	0	0
PS-44	6	2	4	6	4	2
PS-45	85	115	117	117	116	116
PS-46	0	0	0	0	0	0
PS-47	80	80	80	80	80	79
PS-48	537	546	537	519	501	528
PS-49	385	390	400	390	400	395
PS-50	360	355	360	355	370	365
PS-51	37	37	37	37	37	37
PS-52	0	0	0	0	0	0
PS-53	0	0	0	0	0	0
PS-54	0	0	0	0	0	0
PS-55	0	0	0	0	0	0
PS-56	0	0	0	0	0	0
PS-57	0	0	0	0	0	0
PS-58	0	0	0	0	0	0
PS-59	1	1	0	0	0	0
PS-60	43	43	44	44	43	43
PS-61	0	0	0	0	0	0
PS-62	0	0	0	0	0	0

Table B.3. Active Power Dispatch Data in MW from Hour 13 to Hour 18

Gen Name	Hour_13	Hour_14	Hour_15	Hour_16	Hour_17	Hour_18
PS-1	0	0	0	0	0	0
PS-2	4	10	4	1	1	1
PS-3	0	0	0	0	0	0
PS-4	0	0	0	0	0	0
PS-5	282	286	281	276	277	276
PS-6	8	2	2	2	4	2
PS-7	0	0	0	0	0	0
PS-8	405	405	405	405	404	404
PS-9	22	16	7	10	5	5
PS-10	0	0	0	0	0	0
PS-11	647	646	643	655	655	650
PS-12	0	0	0	0	0	0
PS-13	0	0	0	0	0	0
PS-14	0	0	0	0	0	0
PS-15	54	55	54	54	54	54
PS-16	55	55	54	54	54	54
PS-17	2	3	3	1	4	2
PS-18	14	14	22	1	1	7
PS-19	4	4	4	4	3	4
PS-20	4	4	4	3	3	4
PS-21	1	1	1	0	0	1
PS-22	6	1	0	1	2	1
PS-23	0	0	0	0	0	0
PS-24	2	12	5	0	1	1
PS-25	0	0	0	0	0	0
PS-26	0	0	0	0	0	0
PS-27	71	71	71	72	68	68
PS-28	35	34	34	35	34	34
PS-29	0	0	0	0	0	0
PS-30	0	0	0	0	0	0
PS-31	1349	1345	1333	1349	1347	1341
PS-32	0	0	0	0	0	0
PS-33	224	224	224	224	224	224
PS-34	0	0	0	0	0	0
PS-35	43	42	41	43	43	43
PS-36	165	164	168	166	165	165
PS-37	0	0	0	0	0	0
PS-38	39	39	38	38	38	38

Table B.3. (continued)

Gen Name	**Hour_13**	**Hour_14**	**Hour_15**	**Hour_16**	**Hour_17**	**Hour_18**
PS-39	0	1	1	0	0	0
PS-40	96	96	96	95	94	93
PS-41	3	0	2	0	3	2
PS-42	109	108	108	106	106	106
PS-43	1	1	0	0	0	0
PS-44	0	0	0	1	9	2
PS-45	115	115	115	115	115	115
PS-46	0	0	0	0	0	3
PS-47	79	79	78	79	78	78
PS-48	528	528	516	520	531	501
PS-49	390	390	390	400	405	410
PS-50	370	370	355	370	390	380
PS-51	37	37	37	37	37	37
PS-52	0	0	0	0	0	0
PS-53	0	0	0	0	0	0
PS-54	0	0	0	0	0	0
PS-55	0	0	0	0	0	0
PS-56	0	0	0	0	0	0
PS-57	0	0	0	0	0	0
PS-58	0	0	0	0	0	0
PS-59	1	0	0	0	0	0
PS-60	44	43	44	43	43	43
PS-61	0	12	11	7	6	4
PS-62	0	0	0	0	0	0

Table B.4. Active Power Dispatch Data in MW from Hour 19 to Hour 24

Gen Name	Hour_19	Hour_20	Hour_21	Hour_22	Hour_23	Hour_24
PS-1	0	0	0	0	0	0
PS-2	1	2	7	7	3	5
PS-3	0	0	0	0	0	0
PS-4	0	0	0	0	0	0
PS-5	282	283	283	290	292	289
PS-6	5	11	9	8	4	7
PS-7	0	0	0	0	0	0
PS-8	404	405	403	405	404	404
PS-9	5	22	22	10	8	8
PS-10	0	0	0	0	0	0
PS-11	650	655	651	650	650	656
PS-12	0	0	0	0	0	0
PS-13	0	0	0	0	0	0
PS-14	0	0	0	0	0	0
PS-15	54	54	54	54	54	64
PS-16	54	55	55	56	56	59
PS-17	1	1	0	0	0	2
PS-18	11	20	50	35	43	16
PS-19	10	17	5	3	1	2
PS-20	3	1	1	1	1	2
PS-21	0	1	0	0	0	3
PS-22	5	28	27	20	5	5
PS-23	0	0	0	0	0	0
PS-24	1	1	1	0	0	0
PS-25	0	0	0	0	0	0
PS-26	0	0	0	0	0	0
PS-27	68	71	39	37	37	38
PS-28	34	34	34	35	35	34
PS-29	0	0	0	0	0	0
PS-30	0	0	0	0	0	0
PS-31	1322	1325	1331	1296	1341	1354
PS-32	0	0	0	0	0	0
PS-33	224	224	224	224	224	224
PS-34	0	0	0	0	0	0
PS-35	43	43	43	43	43	39
PS-36	168	166	165	165	130	128
PS-37	0	0	0	0	0	0
PS-38	38	39	39	40	40	35

Table B.4. (continued)

Gen Name	Hour_19	Hour_20	Hour_21	Hour_22	Hour_23	Hour_24
PS-39	0	2	2	2	2	0
PS-40	94	96	98	99	99	99
PS-41	1	0	10	8	1	4
PS-42	106	107	107	110	112	112
PS-43	0	1	2	3	1	1
PS-44	0	0	13	26	7	8
PS-45	115	116	116	115	111	0
PS-46	0	0	0	1	1	1
PS-47	78	78	79	79	79	81
PS-48	516	519	519	520	520	513
PS-49	410	400	400	400	400	400
PS-50	380	385	380	380	380	385
PS-51	37	37	37	37	37	37
PS-52	0	0	0	0	0	0
PS-53	0	0	0	0	0	0
PS-54	0	0	0	0	0	0
PS-55	0	0	0	0	0	0
PS-56	0	0	0	0	0	0
PS-57	0	0	0	0	0	0
PS-58	0	0	0	0	0	0
PS-59	0	1	0	1	1	0
PS-60	43	44	44	44	44	43
PS-61	1	1	1	1	1	-2
PS-62	0	0	0	0	0	0

APPENDIX – C

VOLTAGE SETPOINTS OF POWER PLANTS

C.1 Voltage Setpoints Of Power Plants For Scenario 1

Table C.1.1. Voltage Setpoint Values in kV from Hour 1 to Hour 6

Gen Name	Hour_1	Hour_2	Hour_3	Hour_4	Hour_5	Hour_6
PS-1	-	-	-	-	-	-
PS-2	33.122	33.214	33.284	33.370	33.222	33.341
PS-3	-	-	-	-	-	-
PS-4	-	-	-	-	-	-
PS-5	156.494	156.409	156.411	156.426	156.403	156.405
PS-6	34.561	34.547	34.554	34.561	34.587	34.572
PS-7	-	-	-	-	-	-
PS-8	400.677	399.796	399.524	399.487	399.482	399.514
PS-9	34.069	34.080	34.088	34.091	34.091	34.246
PS-10	-	-	-	-	-	-
PS-11	402.729	402.327	402.292	402.305	402.307	402.241
PS-12	-	-	-	-	-	-
PS-13	-	-	-	-	-	-
PS-14	-	-	-	-	-	-
PS-15	153.476	154.319	155.044	155.212	155.231	155.060
PS-16	154.659	154.810	154.914	154.943	154.893	154.906
PS-17	-	-	22.006	22.000	-	22.008
PS-18	19.847	19.872	19.889	19.893	19.893	19.890
PS-19	-	22.107	22.116	22.142	22.142	22.117
PS-20	-	-	-	-	22.105	22.109
PS-21	-	-	-	-	-	-
PS-22	33.228	33.231	33.230	33.229	33.233	33.238
PS-23	-	-	-	-	-	-
PS-24	34.500	34.500	34.500	34.500	34.500	34.500

Table C.1.1. (continued)

Gen Name	Hour_1	Hour_2	Hour_3	Hour_4	Hour_5	Hour_6
PS-25	-	-	-	-	-	-
PS-26	-	-	-	-	-	-
PS-27	156.113	156.192	156.283	156.323	156.322	156.265
PS-28	34.377	34.398	34.401	34.405	34.404	34.404
PS-29	-	-	-	-	-	-
PS-30	-	-	-	-	-	-
PS-31	392.123	391.525	391.695	391.779	391.845	391.615
PS-32	-	-	-	-	-	-
PS-33	155.019	155.156	155.287	155.327	155.337	155.263
PS-34	-	-	-	-	-	-
PS-35	32.739	32.841	32.925	32.959	32.967	32.940
PS-36	34.408	34.467	34.488	34.496	34.493	34.493
PS-37	-	-	-	-	-	-
PS-38	33.768	33.801	33.840	33.856	33.858	33.844
PS-39	22.000	22.000	22.000	22.000	22.000	22.000
PS-40	155.029	155.188	155.392	155.477	155.485	155.410
PS-41	-	-	-	-	-	31.500
PS-42	10.816	10.844	10.855	10.860	10.855	10.854
PS-43	-	31.250	31.250	31.250	31.250	-
PS-44	33.846	33.838	-	-	-	33.843
PS-45	154.976	155.080	155.188	155.146	155.141	155.100
PS-46	31.250	31.250	31.250	31.250	-	-
PS-47	34.167	34.205	34.230	34.239	34.236	34.229
PS-48	392.829	391.955	392.578	392.894	392.740	392.325
PS-49	394.289	392.955	393.260	393.480	393.389	393.187
PS-50	393.287	392.433	393.015	393.312	393.177	392.770
PS-51	157.542	156.993	157.181	157.326	157.311	157.133
PS-52	-	-	-	-	-	-
PS-53	-	-	-	-	-	-
PS-54	-	-	-	-	-	-
PS-55	-	-	-	-	-	-
PS-56	-	-	-	-	-	-
PS-57	-	-	-	-	-	-
PS-58	-	-	-	-	-	-
PS-59	-	-	-	22.000	22.000	22.000
PS-60	159.168	159.162	159.449	159.584	159.591	159.445
PS-61	-	-	-	-	-	-
PS-62	-	-	-	-	-	-

Table C.1.2. Voltage Setpoint Values in kV from Hour 7 to Hour 12

Gen Name	Hour_7	Hour_8	Hour_9	Hour_10	Hour_11	Hour_12
PS-1	-	-	-	-	-	-
PS-2	33.211	33.067	32.740	32.475	32.320	32.353
PS-3	-	-	-	-	-	-
PS-4	-	-	-	-	-	-
PS-5	156.412	156.381	156.407	156.481	156.464	156.511
PS-6	34.587	34.561	34.564	34.402	34.409	34.452
PS-7	-	-	-	-	-	-
PS-8	399.705	399.958	401.441	401.889	402.021	402.532
PS-9	34.112	34.105	34.244	34.335	34.172	34.139
PS-10	-	-	-	-	-	-
PS-11	402.273	402.385	404.002	403.721	404.085	404.612
PS-12	-	-	-	-	-	-
PS-13	-	-	-	-	-	-
PS-14	-	-	-	-	-	-
PS-15	154.506	153.859	154.331	153.193	153.287	153.452
PS-16	154.854	154.766	154.506	154.423	154.344	154.286
PS-17	21.997	22.007	21.992	22.024	21.995	21.970
PS-18	19.883	19.883	19.884	19.920	19.901	19.908
PS-19	22.133	22.103	22.200	22.187	22.187	22.188
PS-20	22.075	-	22.047	22.075	22.105	22.126
PS-21	-	6.300	6.300	-	-	-
PS-22	33.251	33.262	33.285	33.290	33.315	33.351
PS-23	-	-	-	-	-	-
PS-24	34.500	34.500	34.500	34.500	34.500	34.500
PS-25	-	-	-	-	-	-
PS-26	-	-	-	-	-	-
PS-27	156.193	156.201	156.782	156.503	156.670	156.818
PS-28	34.402	34.405	34.442	34.428	34.438	34.446
PS-29	-	-	-	-	-	-
PS-30	-	-	-	-	-	-
PS-31	391.582	391.688	394.963	393.364	394.462	395.648
PS-32	-	-	-	-	-	-
PS-33	155.177	155.109	155.506	155.060	155.224	155.385
PS-34	-	-	-	-	-	-
PS-35	32.851	32.749	32.617	32.374	32.355	32.349
PS-36	34.480	34.468	34.504	34.490	34.498	34.497
PS-37	-	-	-	-	-	-
PS-38	33.807	33.776	33.833	33.690	33.708	33.731

Table C.1.2.(continued)

Gen Name	Hour_7	Hour_8	Hour_9	Hour_10	Hour_11	Hour_12
PS-39	22.000	-	-	-	-	22.000
PS-40	155.228	155.101	155.496	154.947	155.065	155.180
PS-41	31.500	31.500	31.500	-	-	31.500
PS-42	10.850	10.858	10.915	10.945	10.956	10.959
PS-43	-	-	-	-	-	-
PS-44	33.869	33.843	33.920	33.908	33.917	33.909
PS-45	155.001	155.035	155.445	155.123	155.233	155.339
PS-46	-	-	-	-	-	-
PS-47	34.215	34.216	34.302	34.292	34.311	34.325
PS-48	392.278	393.966	401.687	399.092	400.354	401.238
PS-49	393.097	394.329	400.772	398.697	399.780	400.665
PS-50	392.695	394.251	401.940	399.198	400.484	401.385
PS-51	157.039	157.529	159.776	158.601	158.999	159.277
PS-52	-	-	-	-	-	-
PS-53	-	-	-	-	-	-
PS-54	-	-	-	-	-	-
PS-55	-	-	-	-	-	-
PS-56	-	-	-	-	-	-
PS-57	-	-	-	-	-	-
PS-58	-	-	-	-	-	-
PS-59	22.000	22.000	-	-	-	-
PS-60	159.227	159.248	160.523	159.143	159.413	159.684
PS-61	-	-	-	-	-	-
PS-62	-	-	-	-	-	-

Table C.1.3. Voltage Setpoint Values in kV from Hour 13 to Hour 18

Gen Name	Hour_13	Hour_14	Hour_15	Hour_16	Hour_17	Hour_18
PS-1	-	-	-	-	-	-
PS-2	32.469	32.725	32.423	32.209	31.983	31.714
PS-3	-	-	-	-	-	-
PS-4	-	-	-	-	-	-
PS-5	156.540	156.527	156.583	156.590	156.499	156.378
PS-6	34.570	34.444	34.456	34.438	34.437	34.331
PS-7	-	-	-	-	-	-
PS-8	402.013	402.417	402.588	402.331	402.678	403.397
PS-9	34.421	34.236	33.951	34.045	33.852	34.557
PS-10	-	-	-	-	-	-
PS-11	403.758	404.232	404.488	404.391	406.122	407.540
PS-12	-	-	-	-	-	-
PS-13	-	-	-	-	-	-
PS-14	-	-	-	-	-	-
PS-15	153.073	153.241	153.252	153.294	154.200	155.287
PS-16	154.392	154.336	154.321	154.353	154.183	154.084
PS-17	21.978	21.983	21.981	21.967	21.982	21.958
PS-18	19.911	19.910	19.912	19.890	19.864	19.851
PS-19	22.164	22.164	22.163	22.165	22.138	22.180
PS-20	22.128	22.126	22.125	22.104	22.097	22.118
PS-21	6.300	6.300	6.300	-	-	6.300
PS-22	33.305	33.289	-	33.294	33.331	33.368
PS-23	-	-	-	-	-	-
PS-24	34.500	34.500	34.500	-	34.500	34.500
PS-25	-	-	-	-	-	-
PS-26	-	-	-	-	-	-
PS-27	156.436	156.588	156.601	156.675	157.438	158.393
PS-28	34.421	34.428	34.427	34.439	34.488	34.559
PS-29	-	-	-	-	-	-
PS-30	-	-	-	-	-	-
PS-31	393.117	394.089	394.236	394.620	399.976	402.640
PS-32	-	-	-	-	-	-
PS-33	155.022	155.150	155.154	155.241	156.060	156.879
PS-34	-	-	-	-	-	-
PS-35	32.383	32.362	32.361	32.351	32.396	32.576
PS-36	34.479	34.486	34.484	34.491	34.520	34.707
PS-37	-	-	-	-	-	-
PS-38	33.688	33.701	33.700	33.708	33.837	34.039

Table C.1.3. (continued)

Gen Name	**Hour_13**	**Hour_14**	**Hour_15**	**Hour_16**	**Hour_17**	**Hour_18**
PS-39	-	22.000	22.000	-	-	-
PS-40	154.908	155.008	155.013	155.063	155.712	156.814
PS-41	31.500	-	31.500	-	31.500	31.500
PS-42	10.937	10.949	10.949	10.955	10.978	11.116
PS-43	31.250	31.250	-	-	-	-
PS-44	-	-	-	33.894	34.000	34.050
PS-45	155.084	155.185	155.190	155.239	155.791	156.667
PS-46	-	-	-	-	-	31.250
PS-47	34.283	34.301	34.302	34.311	34.383	34.573
PS-48	398.564	400.049	400.240	400.525	403.149	404.143
PS-49	398.340	399.572	399.782	399.989	402.699	403.928
PS-50	398.660	400.166	400.363	400.653	403.361	404.377
PS-51	158.453	158.899	158.965	159.053	159.798	160.135
PS-52	-	-	-	-	-	-
PS-53	-	-	-	-	-	-
PS-54	-	-	-	-	-	-
PS-55	-	-	-	-	-	-
PS-56	-	-	-	-	-	-
PS-57	-	-	-	-	-	-
PS-58	-	-	-	-	-	-
PS-59	22.000	-	-	-	-	-
PS-60	159.069	159.338	159.375	159.460	160.589	161.304
PS-61	-	35.106	35.091	35.011	35.296	34.734
PS-62	-	-	-	-	-	-

Table C.1.4. Voltage Setpoint Values in kV from Hour 19 to Hour 24

Gen Name	Hour_19	Hour_20	Hour_21	Hour_22	Hour_23	Hour_24
PS-1	-	-	-	-	-	-
PS-2	32.141	32.262	32.653	32.756	32.501	32.765
PS-3	-	-	-	-	-	-
PS-4	-	-	-	-	-	-
PS-5	156.533	156.530	156.568	156.541	156.557	156.512
PS-6	34.488	34.596	34.590	34.615	34.520	34.621
PS-7	-	-	-	-	-	-
PS-8	402.637	402.169	402.053	401.978	402.226	401.998
PS-9	33.855	34.382	34.423	34.056	33.988	33.990
PS-10	-	-	-	-	-	-
PS-11	404.949	403.809	403.486	403.419	403.679	404.709
PS-12	-	-	-	-	-	-
PS-13	-	-	-	-	-	-
PS-14	-	-	-	-	-	-
PS-15	153.557	153.169	153.070	153.044	153.075	155.202
PS-16	154.270	154.394	154.454	154.469	154.457	154.430
PS-17	21.961	21.970	-	-	-	21.976
PS-18	19.899	19.916	19.953	19.931	19.949	19.868
PS-19	22.307	22.491	22.185	22.133	22.086	22.120
PS-20	22.101	22.052	22.053	22.051	22.052	22.063
PS-21	-	6.300	-	-	-	6.300
PS-22	33.325	33.429	33.412	33.371	33.295	33.303
PS-23	-	-	-	-	-	-
PS-24	34.500	34.500	34.500	-	-	-
PS-25	-	-	-	-	-	-
PS-26	-	-	-	-	-	-
PS-27	156.897	156.558	156.315	156.244	156.266	156.839
PS-28	34.449	34.427	34.418	34.417	34.416	34.449
PS-29	-	-	-	-	-	-
PS-30	-	-	-	-	-	-
PS-31	396.356	393.910	392.989	392.709	392.818	396.366
PS-32	-	-	-	-	-	-
PS-33	155.473	155.128	154.980	154.920	154.957	155.681
PS-34	-	-	-	-	-	-
PS-35	32.349	32.354	32.391	32.415	32.403	32.654
PS-36	34.496	34.486	34.480	34.472	34.461	34.494
PS-37	-	-	-	-	-	-
PS-38	33.743	33.696	33.688	33.690	33.690	33.860

Table C.1.4. (continued)

Gen Name	**Hour_19**	**Hour_20**	**Hour_21**	**Hour_22**	**Hour_23**	**Hour_24**
PS-39	-	22.000	22.000	22.000	22.000	-
PS-40	155.239	154.966	154.908	154.886	154.901	155.699
PS-41	31.500	-	31.500	31.500	31.500	31.500
PS-42	10.962	10.948	10.937	10.925	10.927	10.922
PS-43	-	31.250	31.250	31.250	31.250	31.250
PS-44	-	-	33.934	34.001	33.895	33.944
PS-45	155.398	155.166	155.081	155.040	155.061	-
PS-46	-	-	-	31.250	31.250	31.250
PS-47	34.332	34.297	34.281	34.270	34.275	34.327
PS-48	401.622	399.826	398.392	397.531	397.971	402.077
PS-49	401.053	399.355	398.172	397.521	397.890	401.567
PS-50	401.779	399.938	398.484	397.622	398.060	402.290
PS-51	159.391	158.840	158.387	158.127	158.271	160.100
PS-52	-	-	-	-	-	-
PS-53	-	-	-	-	-	-
PS-54	-	-	-	-	-	-
PS-55	-	-	-	-	-	-
PS-56	-	-	-	-	-	-
PS-57	-	-	-	-	-	-
PS-58	-	-	-	-	-	-
PS-59	-	22.000	-	22.000	22.000	-
PS-60	159.838	159.289	159.045	158.946	158.993	160.819
PS-61	34.959	34.799	34.730	34.702	34.715	35.300
PS-62	-	-	-	-	-	-

C.2 Voltage Setpoints Of Power Plants For Scenario 2

Table C.2.1. Voltage Setpoint Values in kV from Hour 1 to Hour 6

Gen Name	Hour_1	Hour_2	Hour_3	Hour_4	Hour_5	Hour_6
PS-1	-	-	-	-	-	-
PS-2	33.127	33.219	33.287	33.388	33.224	33.344
PS-3	-	-	-	-	-	-
PS-4	-	-	-	-	-	-
PS-5	156.473	156.396	156.385	156.508	156.375	156.382
PS-6	34.561	34.548	34.552	34.572	34.585	34.571
PS-7	-	-	-	-	-	-
PS-8	401.026	400.133	399.757	400.457	399.674	399.745
PS-9	34.064	34.076	34.084	34.092	34.086	34.242
PS-10	-	-	-	-	-	-
PS-11	403.796	403.192	402.867	403.846	402.761	402.791
PS-12	-	-	-	-	-	-
PS-13	-	-	-	-	-	-
PS-14	-	-	-	-	-	-
PS-15	153.572	154.226	154.945	155.135	155.161	154.955
PS-16	154.603	154.776	154.881	155.017	154.863	154.877
PS-17	-	-	22.002	22.003	-	22.005
PS-18	19.815	19.850	19.868	19.936	19.874	19.871
PS-19	-	22.116	22.121	22.194	22.147	22.122
PS-20	-	-	-	-	22.102	22.106
PS-21	-	-	-	-	-	-
PS-22	33.248	33.251	33.245	33.446	33.247	33.254
PS-23	-	-	-	-	-	-
PS-24	34.500	34.500	34.500	34.500	34.500	34.500
PS-25	-	-	-	-	-	-
PS-26	-	-	-	-	-	-
PS-27	156.972	156.861	156.772	156.821	156.737	156.735
PS-28	34.428	34.443	34.435	34.488	34.434	34.439
PS-29	-	-	-	-	-	-
PS-30	-	-	-	-	-	-
PS-31	394.862	393.546	392.926	393.167	392.751	392.765
PS-32	-	-	-	-	-	-
PS-33	155.698	155.684	155.647	155.811	155.626	155.609
PS-34	-	-	-	-	-	-
PS-35	32.919	32.978	33.020	33.054	33.044	33.030

Table C.2.1. (continued)

Gen Name	**Hour_1**	**Hour_2**	**Hour_3**	**Hour_4**	**Hour_5**	**Hour_6**
PS-36	34.578	34.605	34.603	34.610	34.600	34.606
PS-37	-	-	-	-	-	-
PS-38	33.977	33.959	33.953	33.962	33.952	33.951
PS-39	22.000	22.000	22.000	22.000	22.000	22.000
PS-40	155.966	155.905	155.892	155.978	155.898	155.886
PS-41	-	-	-	-	-	31.500
PS-42	10.918	10.927	10.923	10.928	10.918	10.920
PS-43	-	31.250	31.250	31.250	31.250	-
PS-44	33.917	33.892	-	-	-	33.885
PS-45	155.814	155.728	155.669	155.608	155.549	155.559
PS-46	31.250	31.250	31.250	31.250	-	-
PS-47	34.323	34.327	34.324	34.334	34.319	34.320
PS-48	394.631	393.588	393.569	393.544	393.511	393.338
PS-49	395.964	394.395	394.115	394.125	394.033	394.042
PS-50	395.077	394.030	393.987	393.976	393.930	393.755
PS-51	157.293	156.892	157.005	157.075	157.104	156.967
PS-52	-	-	-	-	-	-
PS-53	-	-	-	-	-	-
PS-54	-	-	-	-	-	-
PS-55	-	-	-	-	-	-
PS-56	-	-	-	-	-	-
PS-57	-	-	-	-	-	-
PS-58	-	-	-	-	-	-
PS-59	-	-	-	22	22	22
PS-60	159.8171	159.6528	159.6933	159.8139	159.74	159.6771
PS-61	-	-	-	-	-	-
PS-62	-	-	-	-	-	-

Table C.2.2. Voltage Setpoint Values in kV from Hour 7 to Hour 12

Gen Name	Hour_7	Hour_8	Hour_9	Hour_10	Hour_11	Hour_12
PS-1	-	-	-	-	-	-
PS-2	33.216	33.091	32.742	32.481	32.328	32.357
PS-3	-	-	-	-	-	-
PS-4	-	-	-	-	-	-
PS-5	156.394	156.474	156.327	156.290	156.231	156.244
PS-6	34.587	34.577	34.561	34.395	34.398	34.436
PS-7	-	-	-	-	-	-
PS-8	400.030	401.182	401.652	402.636	402.874	403.384
PS-9	34.108	34.107	34.236	34.316	34.147	34.110
PS-10	-	-	-	-	-	-
PS-11	403.110	404.792	405.534	407.045	407.478	407.920
PS-12	-	-	-	-	-	-
PS-13	-	-	-	-	-	-
PS-14	-	-	-	-	-	-
PS-15	154.391	153.886	154.051	153.573	153.711	153.848
PS-16	154.818	154.824	154.381	154.104	153.955	153.833
PS-17	21.993	22.009	21.980	21.994	21.959	21.929
PS-18	19.861	19.914	19.830	19.788	19.746	19.735
PS-19	22.141	22.163	22.198	22.188	22.180	22.166
PS-20	22.071	-	22.035	22.045	22.069	22.084
PS-21	-	6.300	6.300	-	-	-
PS-22	33.270	33.519	33.297	33.341	33.376	33.415
PS-23	-	-	-	-	-	-
PS-24	34.500	34.500	34.500	34.500	34.500	34.500
PS-25	-	-	-	-	-	-
PS-26	-	-	-	-	-	-
PS-27	156.841	157.113	157.682	159.219	159.855	160.241
PS-28	34.446	34.512	34.478	34.562	34.602	34.627
PS-29	-	-	-	-	-	-
PS-30	-	-	-	-	-	-
PS-31	393.527	395.320	400.017	403.197	403.949	404.557
PS-32	-	-	-	-	-	-
PS-33	155.686	156.032	156.411	157.324	157.862	158.310
PS-34	-	-	-	-	-	-
PS-35	32.981	32.938	32.808	33.026	33.114	33.161
PS-36	34.615	34.617	34.591	34.906	35.045	35.123
PS-37	-	-	-	-	-	-
PS-38	33.958	33.980	34.054	34.411	34.567	34.674

Table C.2.2.(continued)

Gen Name	Hour_7	Hour_8	Hour_9	Hour_10	Hour_11	Hour_12
PS-39	22.000	-	-	-	-	22.000
PS-40	155.915	156.079	156.474	158.292	158.973	159.367
PS-41	31.500	31.500	31.500	-	-	31.500
PS-42	10.930	10.950	10.970	11.207	11.291	11.338
PS-43	-	-	-	-	-	-
PS-44	33.926	33.954	33.980	34.113	34.174	34.181
PS-45	155.625	155.860	156.239	157.739	158.415	158.885
PS-46	-	-	-	-	-	-
PS-47	34.331	34.362	34.411	34.729	34.879	34.986
PS-48	393.759	395.057	401.267	401.361	402.247	402.677
PS-49	394.420	395.663	401.181	401.904	402.703	403.194
PS-50	394.153	395.409	401.530	401.658	402.550	402.965
PS-51	156.928	157.338	159.701	157.991	158.367	158.695
PS-52	-	-	-	-	-	-
PS-53	-	-	-	-	-	-
PS-54	-	-	-	-	-	-
PS-55	-	-	-	-	-	-
PS-56	-	-	-	-	-	-
PS-57	-	-	-	-	-	-
PS-58	-	-	-	-	-	-
PS-59	22	22	-	-	-	-
PS-60	159.6769	159.8755	160.8514	161.0077	161.1856	161.2874
PS-61	-	-	-	-	-	-
PS-62	-	-	-	-	-	-

Table C.2.3. Voltage Setpoint Values in kV from Hour 13 to Hour 18

Gen Name	Hour_13	Hour_14	Hour_15	Hour_16	Hour_17	Hour_18
PS-1	-	-	-	-	-	-
PS-2	32.475	32.730	32.425	32.214	31.568	31.429
PS-3	-	-	-	-	-	-
PS-4	-	-	-	-	-	-
PS-5	156.368	156.320	156.351	156.371	154.069	153.566
PS-6	34.565	34.436	34.444	34.428	34.310	34.214
PS-7	-	-	-	-	-	-
PS-8	402.682	403.142	403.172	403.109	402.577	402.487
PS-9	34.403	34.214	33.930	34.023	34.561	34.529
PS-10	-	-	-	-	-	-
PS-11	407.001	407.512	407.759	407.687	410.462	411.291
PS-12	-	-	-	-	-	-
PS-13	-	-	-	-	-	-
PS-14	-	-	-	-	-	-
PS-15	153.418	153.613	153.617	153.677	154.512	155.367
PS-16	154.090	153.979	153.929	153.976	153.146	152.376
PS-17	21.949	21.950	21.945	21.932	21.931	21.855
PS-18	19.789	19.769	19.761	19.739	19.665	19.562
PS-19	22.165	22.158	22.148	22.155	22.072	22.002
PS-20	22.099	22.093	22.088	22.069	22.063	22.030
PS-21	6.300	6.300	6.300	-	-	6.300
PS-22	33.347	33.339	-	33.349	33.468	33.486
PS-23	-	-	-	-	-	-
PS-24	34.500	34.500	34.500	-	34.500	34.500
PS-25	-	-	-	-	-	-
PS-26	-	-	-	-	-	-
PS-27	158.912	159.481	159.554	159.755	160.924	161.351
PS-28	34.531	34.559	34.550	34.595	34.704	34.677
PS-29	-	-	-	-	-	-
PS-30	-	-	-	-	-	-
PS-31	402.956	403.748	403.895	404.062	406.059	406.789
PS-32	-	-	-	-	-	-
PS-33	157.111	157.466	157.482	157.788	159.485	160.490
PS-34	-	-	-	-	-	-
PS-35	32.977	33.059	33.072	33.090	33.230	33.283
PS-36	34.834	34.953	34.967	35.013	35.285	35.462
PS-37	-	-	-	-	-	-
PS-38	34.344	34.479	34.497	34.541	34.896	35.080

Table C.2.3. (continued)

Gen Name	Hour_13	Hour_14	Hour_15	Hour_16	Hour_17	Hour_18
PS-39	-	22.000	22.000	-	-	-
PS-40	157.950	158.590	158.672	158.866	160.033	160.477
PS-41	31.500	-	31.500	-	31.500	31.500
PS-42	11.162	11.240	11.249	11.276	11.426	11.484
PS-43	31.250	31.250	-	-	-	-
PS-44	-	-	-	34.117	34.383	34.399
PS-45	157.439	158.018	158.102	158.304	159.952	160.882
PS-46	-	-	-	-	-	31.250
PS-47	34.663	34.787	34.803	34.851	35.251	35.494
PS-48	400.844	402.184	402.312	402.514	403.785	404.225
PS-49	401.537	402.650	402.819	402.943	404.306	404.728
PS-50	401.136	402.475	402.611	402.806	404.045	404.443
PS-51	157.877	158.318	158.377	158.477	159.589	160.067
PS-52	-	-	-	-	-	-
PS-53	-	-	-	-	-	-
PS-54	-	-	-	-	-	-
PS-55	-	-	-	-	-	-
PS-56	-	-	-	-	-	-
PS-57	-	-	-	-	-	-
PS-58	-	-	-	-	-	-
PS-59	22	-	-	-	-	-
PS-60	160.9173	161.1207	161.1469	161.1878	161.4734	161.5936
PS-61	-	34.86627	34.83021	34.69291	34.35165	34.04753
PS-62	-	-	-	-	-	-

Table C.2.4. Voltage Setpoint Values in kV from Hour 19 to Hour 24

Gen Name	Hour_19	Hour_20	Hour_21	Hour_22	Hour_23	Hour_24
PS-1	-	-	-	-	-	-
PS-2	32.144	32.274	32.661	32.762	32.506	32.766
PS-3	-	-	-	-	-	-
PS-4	-	-	-	-	-	-
PS-5	156.254	156.351	156.409	156.393	156.393	156.443
PS-6	34.471	34.592	34.587	34.612	34.515	34.618
PS-7	-	-	-	-	-	-
PS-8	403.474	403.061	402.775	402.601	402.828	402.135
PS-9	33.828	34.358	34.405	34.040	33.971	33.983
PS-10	-	-	-	-	-	-
PS-11	408.140	407.296	406.770	406.552	406.829	405.918
PS-12	-	-	-	-	-	-
PS-13	-	-	-	-	-	-
PS-14	-	-	-	-	-	-
PS-15	153.925	153.562	153.407	153.332	153.378	154.747
PS-16	153.789	154.062	154.164	154.198	154.165	154.318
PS-17	21.918	21.939	-	-	-	21.965
PS-18	19.722	19.785	19.841	19.826	19.838	19.822
PS-19	22.293	22.554	22.191	22.134	22.082	22.112
PS-20	22.057	22.020	22.025	22.025	22.024	22.052
PS-21	-	6.300	-	-	-	6.300
PS-22	33.388	33.496	33.461	33.408	33.331	33.308
PS-23	-	-	-	-	-	-
PS-24	34.500	34.500	34.500	-	-	-
PS-25	-	-	-	-	-	-
PS-26	-	-	-	-	-	-
PS-27	160.342	159.435	158.698	158.348	158.506	157.596
PS-28	34.616	34.568	34.536	34.515	34.519	34.474
PS-29	-	-	-	-	-	-
PS-30	-	-	-	-	-	-
PS-31	404.782	403.660	402.790	402.323	402.550	400.454
PS-32	-	-	-	-	-	-
PS-33	158.301	157.464	157.050	156.844	156.936	156.410
PS-34	-	-	-	-	-	-
PS-35	33.167	33.047	32.958	32.909	32.931	32.811
PS-36	35.143	34.947	34.814	34.738	34.760	34.567
PS-37	-	-	-	-	-	-
PS-38	34.703	34.466	34.315	34.239	34.277	34.047

Table C.2.4. (continued)

Gen Name	**Hour_19**	**Hour_20**	**Hour_21**	**Hour_22**	**Hour_23**	**Hour_24**
PS-39	-	22.000	22.000	22.000	22.000	-
PS-40	159.463	158.526	157.811	157.406	157.604	156.501
PS-41	31.500	-	31.500	31.500	31.500	31.500
PS-42	11.350	11.236	11.145	11.089	11.112	10.965
PS-43	-	31.250	31.250	31.250	31.250	31.250
PS-44	-	-	34.135	34.221	34.057	33.992
PS-45	159.025	157.970	157.328	156.994	157.156	-
PS-46	-	-	-	31.250	31.250	31.250
PS-47	35.018	34.777	34.638	34.566	34.598	34.412
PS-48	403.134	402.034	400.827	399.958	400.417	401.777
PS-49	403.545	402.499	401.454	400.754	401.160	401.902
PS-50	403.426	402.324	401.114	400.247	400.702	401.983
PS-51	158.892	158.252	157.859	157.664	157.767	160.030
PS-52	-	-	-	-	-	-
PS-53	-	-	-	-	-	-
PS-54	-	-	-	-	-	-
PS-55	-	-	-	-	-	-
PS-56	-	-	-	-	-	-
PS-57	-	-	-	-	-	-
PS-58	-	-	-	-	-	-
PS-59	-	22	-	22	22	-
PS-60	161.3294	161.1035	160.8909	160.7476	160.8228	160.9706
PS-61	34.4088	34.55402	34.59893	34.61137	34.60519	35.29734
PS-62	-	-	-	-	-	-

APPENDIX – D

REDISPATCHED POWER PLANTS

Table D.1. Change in Active Power Outputs in MW of Redispatched Power Plants for Scenario 1

	PS-5	**PS-8**	**PS-9**	**PS-37**	**PS-39**	**PS-41**	**PS-50**	**PS-52**
Hour_10	-	-19	-	-	-	-	-	19
Hour_11	-	-19	-	-	-	-	-	19
Hour_12	-	-87	-	-	33	35	-	19
Hour_13	-	-19	-	-	-	-	-	19
Hour_14	-	-51	-	-	33	-	-	19
Hour_15	-	-86	-	-	33	34	-	19
Hour_16	-	-19	-	-	-	-	-	19
Hour_17	-	-	-	-	-	15	-34	19
Hour_18	23	-	23	28	16	34	-142	19
Hour_19	-	-54	-	-	-	35	-	19
Hour_20	-	-5-	-	-	32	-	-	19
Hour_21	-	-5-	-	-	32	-	-	19
Hour_22	-	-5-	-	-	32	-	-	19
Hour_23	-	-86	-	-	32	35	-	19

Table D.2. Change in Active Power Outputs in MW of Redispatched Power Plants for Scenario 2

	PS-5	**PS-8**	**PS-9**	**PS-12**	**PS-23**	**PS-31**	**PS-37**	**PS-39**	**PS-41**	**PS-50**	**PS-52**
Hour_10	-	-19	-	-	-	-	-	-	-	-	19
Hour_11	-	-19	-	-	-	-	-	-	-	-	19
Hour_12	-	-87	-	-	-	-	-	33	35	-	19
Hour_13	-	-19	-	-	-	-	-	-	-	-	19
Hour_14	-	-51	-	-	-	-	-	33	-	-	19
Hour_15	-	-86	-	-	-	-	-	33	34	-	19
Hour_16	-	-19	-	-	-	-	-	-	-	-	19
Hour_17	207	-	23	78	432	-835	28	16	33	-	19
Hour_18	191	-	23	78	432	-820	28	16	34	-	19
Hour_19	-	-54	-	-	-	-	-	-	35	-	19
Hour_20	-	-5-	-	-	-	-	-	32	-	-	19
Hour_21	-	-5-	-	-	-	-	-	32	-	-	19
Hour_22	-	-5-	-	-	-	-	-	32	-	-	19
Hour_23	-	-86	-	-	-	-	-	32	35	-	19