

Güneş Enerji Santralinin Reaktif Güç Desteği için Kullanılması

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Makale Bilgisi	ÖZET
<p>Geliş Tarihi: 28.06.2024 Kabul Tarihi: 20.11.2024 Yayın Tarihi: 31.08.2025</p> <p>Anahtar Kelimeler: GES, Kompanzasyon, Reaktif güç desteği.</p>	<p>Enerji üretim, iletim ve dağıtım sistemlerinde reaktif güç kompanzasyonu için yatırım yapılmaktadır. Mevcutta elektrik dağıtım şirketleri reaktif güç kompanzasyonu için reaktör, kapasitör ve manyetik kontrollü reaktör yatırımı yapmaktadır. İletim şirketleri ise bu yatırımlara ek olarak mevcutta bulunann üretim santrallerinden yan hizmetler kapsamında reaktif güç desteği almaktadır. Günümüzde güneş enerji santrali (GES), rüzgâr enerji santrali (RES) gibi dağıtık üretim tesislerinin artmasıyla birlikte dağıtım şebekesine bağlı enerji akışı çift yönlü hale gelmiştir. GES ve RES gibi dağıtık üretim tesislerinde üretim olmadığı saatlerde iletkenlerden kaynaklı kapasitif reaktifin artmasına ve üretimin artması ise bölgede gerilim yükselmesine neden olur. Bu çalışmada dağıtık enerji kaynaklarının dezavantajlarını avantaja çevirmek, kompanzasyon yatırım maliyetlerini azaltmak amacıyla GES'lerin reaktif güç kompanzasyonu için kullanılabilirliği araştırılmıştır. Bunun için bir elektrik dağıtım bölgesinde bulunan bir trafo merkezine bağlı bir GES'nden reaktif güç desteği alınması için gerekli simülasyon çalışmaları yapılmıştır. Daha sonra bölgedeki GES'nden yedi saat boyunca reaktif güç desteği alınarak deneysel çalışmalar yapılmıştır. Sonuç olarak GES'nden alınan reaktif güç desteği sayesinde kompanzasyon yatırımlarının azalacağı vurgulanmıştır.</p>

Using Solar Power Plant for Reactive Power Support

Article Info	ABSTRACT
<p>Received: 28.06.2024 Accepted: 20.11.2024 Published: 31.08.2025</p> <p>Keywords: SPP, Compensation, Reactive power support.</p>	<p>Reactive power compensation investments are made for energy production, transmission and distribution systems. Currently, electricity distribution companies invest in reactors, capacitors and magnetically controlled reactors for reactive power compensation. With these investments, transmission companies receive reactive power support from existing production plants within the scope of ancillary services. Nowadays, with the increase in distributed generation facilities such as solar power plants (SPPs) and wind power plants (WPP), the energy flow connected to the distribution grid has become bidirectional. In distributed generation facilities such as SPP and WPP, during hours when there is no production, the capacitive reactive originating from the conductors increases and the increase in production causes voltage rise in the region. In this study, the usability of SPPs for reactive power compensation was investigated in order to turn the disadvantages of distributed energy resources into advantages and to reduce compensation investment costs. For this purpose, necessary simulation studies were carried out to obtain reactive power support from a solar power plant connected to a transformer center in a electricity distribution region. Later, experimental studies were carried out by receiving reactive power support from the solar power plant in the region for seven hours. As a result, it has been emphasized that the reactive power support received from the solar power plant will reduce compensation investments.</p>

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INTRODUCTION

The main task of electricity distribution companies is to transport the energy received from the transmission level to the end user in a quality and sustainable manner. At all voltage levels in the electrical power system, the voltage value must remain within the specified operating range. The increasing penetration of renewable energy sources and the increasing variability and subsequent uncertainty in the electrical grid cause various operational concerns. [1]. Distributed energy sources, by their nature, may cause voltage level distortions due to their inability to produce energy continuously due to their intermittent operation, and capacitive reactance increases due to the conductors going to the distributed source during periods when they are not producing. In order to operate electricity distribution grids more stable and securely, the concept of obtaining ancillary services from renewable energy sources connected to the distribution grid has become more popular with the increase in renewable energy potential. The trend of obtaining reactive power support from existing renewable energy sources is becoming increasingly widespread in the world. Obtaining ancillary services from generation plants connected to the distribution grid established for electricity generation will provide technical and economic benefits [2]. STATCOM applications are mostly due to the high cost of using power electronic components. In the future, low-cost reliable switches must be used to generate the required reactive power. STATCOM can be integrated into the grid to provide an adaptable reactive power source for loads. Inverters can be called STATCOM products from existing sources [3]. STATCOM is becoming increasingly popular among electrical engineers both at home and abroad due to its many features [4]. Inverters installed with distributed generation systems and rooftop solar systems can support ancillary services such as reactive power compensation, voltage regulation, flicker control, active power filtering and harmonic reduction [5-7]. Variable speed generators and wind turbines have the potential to add inertia to the grid, reduce power losses, provide voltage regulation of the system and assist in frequency control [8-10]. Therefore, in order to control the voltage to compensate for the effects of renewable power plants connected to the distribution grid with compensation investments, it is necessary to first use the reactive power features of inverter-controlled power plants and then check other options. Inverter-based power plants can respond very quickly to regulations in reactive power demands and disruptions in grid voltage [11]. However, while the reactive power support range from PV-based power plants is 5-10% within the power, it can be received at 100% at night [12]. During the night when there is no active power, DC-DC conversion is not used. However, an improved control scheme with an energy storage system can allow the inverter to operate in reactive power mode even without the PV panels harvesting solar energy. The inverter can then be programmed to operate as a VAR compensator to deliver only the required reactive power, which will then regulate the voltage at the load end [13]. By controlling the reactive power, compensation investments made every year will be significantly reduced [14]. In addition, by controlling the voltage, technical losses will be reduced, and energy efficiency will be increased. In this way, grid security will be improved, and voltage limit, line capacity, WPP penetration, capacitor penetration will be increased [15]. While receiving reactive power support as a ancillary service from distributed generation plants, should care to take the necessary reactive power support on whichever feeder the need is. For example, when the transmission transformer requirement is capacitive reactive, this support should not be taken from a feeder with capacitive reactive load, and if care is taken to get it from the feeder with inductive load, feeder-based technical losses will be reduced. Likewise, changes in the reactive power control values of distributed generation sources will significantly increase the voltage quality and security of the grid [16]. Photovoltaic (PV) power plants are a key factor in their integration with the electricity distribution grid. PV plant is a special form of distributed energy resources that can affect the electrical distribution grid and substation. There is a wide variety of compensation products considering the way they deal with the reactive power problem. Inverters, which are among these compensation systems, can provide reactive power according to

demand as automatic control of the power factor [17]. In this study, simulation and experimental studies of obtaining reactive power from PV power plants were carried out by using inverters in PV power plants. Simulation studies show that the problems experienced with the commissioning of a biogas power plant in a selected transmission transformer center have been eliminated thanks to the reactive power support received from the solar power plant. Thus, when reactive power support is received from existing production plants, renewable energy penetration will increase even more. In addition, the most important difference of this study from other studies is that the technical losses between the existing methods and the reactive support from the inverter are given mathematically.

MATERIALS AND METHODS

Study Area

According to Article 14 (Compensation of Reactive Energy) of the Electricity Grid Regulation, the ratio of the inductive reactive energy drawn from the system monthly to the active energy drawn from the system cannot exceed 20%, and the ratio of the capacitive reactive energy given to the system monthly to the active energy drawn from the system cannot exceed 15% [18]. Among the substations from which an electricity distribution company receives energy, a substation was selected whose reactive power was determined not to be within the limit values in the legislation. There are 2 similar 100 MVA transformers in this substation and it is a region where seasonal consumption is intense and distributed generation resources are common. A biogas production plant with an installed power of 10 MW was later added to a transformer in this substation. With the connection of this production plant from the distribution grid to the substation, the system's reactive power ratio was increased and the need for reactive power compensation arose.

A distribution grid receives energy from the substation connected to the transmission operator. Feeders at 31,5 kV voltage level coming from the transformers in this substation enter the distribution center entrance cell of the distribution company. Feeders leaving the distribution center either go to another distribution center or to a transformer to be transmitted to the end user. In this transformer, it is converted from 31,5 kV voltage level to 400 V voltage level and transmitted to electricity consumers. The single line diagram of the feeder coming out of the substation for the pilot region we chose in our study is shown in Figure 1. In this feeder, the transformer center reaches the Solar Power Plant building at the end of the 15-kilometer line.

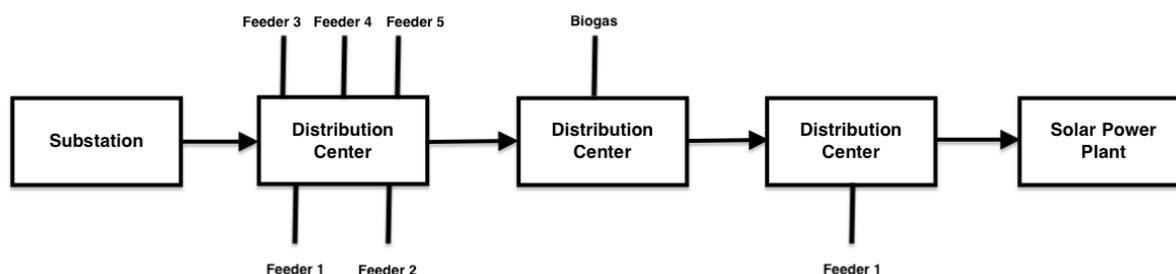


Figure 1
Single line diagram of the supported solar power plant [19].

The power plant from which we will receive reactive power support has 6 solar power plants with a power of 1 MWp and a total installed power of 6 MWp. Each power plant has 3572 solar energy panels with a power of 335 Wp. Each power plant has a PVS800 model 1 MWp central type inverter from ABB and is suitable for receiving reactive support. When field type solar power plants in the distribution region are examined, 1250 kVA transformers and 1 MWp inverters with a total power are used in solar power plants with a typical installed power of 1 MWp. While solar power plants produce at full load;

Although the transformer power is sufficient to obtain reactive power control with a power factor of ± 0.8 , inverter powers may be insufficient. Reactive power support ancillary service can be received from these types of solar power plants when they do not produce at full load.

In order to receive reactive support from solar power plants, the active and reactive power flow in the grid must be effectively monitored and a communication infrastructure must be established. An uninterrupted and high-quality communication infrastructure will enable more flexible operation of distributed energy resources. Remote terminal unit (RTU) installations have been completed from field type SPPs in the electricity distribution region. Effective monitoring can be achieved by connecting the RTU installed in the field to the SCADA control center of electricity distribution company. Within the scope of the study, solar power inverters were manually controlled from the SCADA system according to the reactive power requirement in the substation on the feeder to which they were connected.

Inverters

One way to get maximum benefit from PV plants is to increase the functions performed by the inverter. In addition to the primary task of the inverter, conversion, it also performs multiple functions, including both reactive and real power control. The inverter works as a static compensator (STATCOM) device to generate reactive power to meet the demand generated from the loads and delivers active power to the grid. Inverters can provide reactive power according to demand by changing the power factor. Reactive power demand is provided according to the rule in the graph in Figure 2. In order to receive reactive power support from the inverter, if there is active production P in the production plant, reactive power support with the Q_{max} value according to the graph can be received. When a renewable source is not available, the inverter only acts as a reactive power compensator and provides improvement in power factor [20, 21].

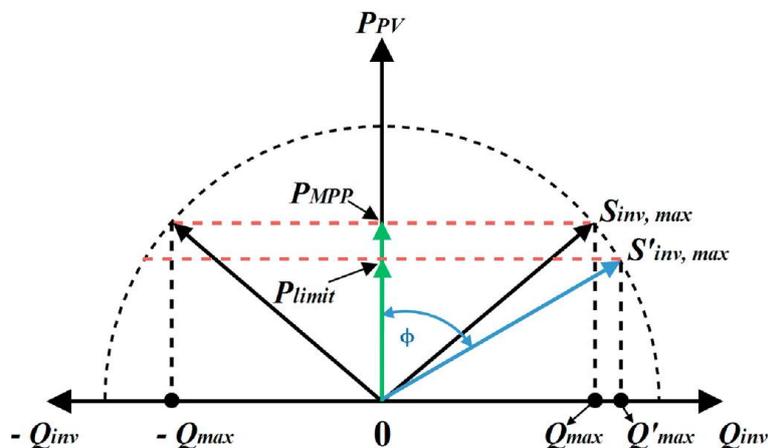


Figure 2

Active power- reactive power capacity table for PV power plant inverter [21].

The equivalent circuit of the grid-connected PV system in Figure 3 consists of a PV array with a capacitor connected in parallel with a diode as the main switch. The capacitor is connected to the power input of the inverter. The inverter output is connected to the grid through the RL filter.

Analysis Program

Within the scope of this study, the DigSilent program, which is a power systems analysis program, was used. Using the analysis program, the load was run on the distribution company feeder using the substation meter data and the approximation ratio of the results of the program was determined. According to the substation meter data and the power system analysis program, the substation in need of reactive power support was determined. The impact of renewable energy sources on this substation

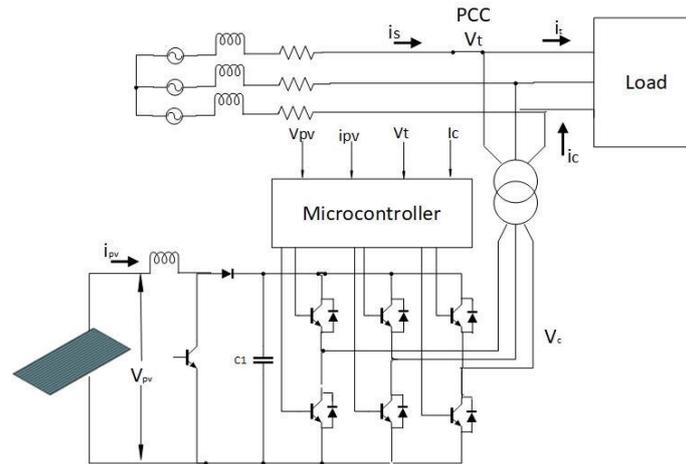


Figure 3
Grid-connected three-phase inverter PV system [22].

and the analysis of the reactive power support to be received from these sources are included under the experimental study title.

RESULTS

System Simulations

System simulations of the feeders of the substation we chose for three cases were carried out with the DigSilent power systems analysis program. In the first two simulations, the reactive power needs of the system were analyzed before and after adding the biogas production facility, while in the third simulation, the reactive power need required for the transformer center to remain within the specified reactive power limits was analyzed after the biogas production facility was connected. In the simulations, data obtained from the real-time transformer center were used to analyze the data. Initially, the accuracy of these data was confirmed by comparing the transformer center values with the simulation results.

Simulation 1: Current Situation

In the first simulation, existing reactive power simulations were performed before connecting the biogas production facility to investigate whether the system needed reagents and whether it met the demands of electricity distribution company. According to the load profile data of the transmission transformer located in the distribution region, which we determined above, the load was run using the power systems analysis program (Figure 4). When the biogas production plant was not in operation, the reactive power ratio we saw in the transmission transformer load profile data was compared with the result of the power systems analysis program. As a result of the simulation, the active power absorbed in the transmission transformer is 12,03 MWp, while the capacitive reactive power appears to be 1,4 MVAR. When the reactive power ratio of the transmission transformer is calculated according to Equation 1, it appears to be 11% capacitive reactive. Since it has a value lower than the 15% limit range, there is no need for an additional compensation investment, according to the regulation.

$$\text{Reactive Power Ratio} = \text{tg}\delta = \frac{Q}{P} = \frac{1,4}{12,03} = 0,11 \quad (1)$$

Simulation 2: Commissioning of the Biogas Production Plant

In the second simulation, reactive power demands in the new situation were examined by performing reactive power simulations after the biogas production facility was included in the substation. The first simulation was repeated after a 10 MWp biogas production power plant was

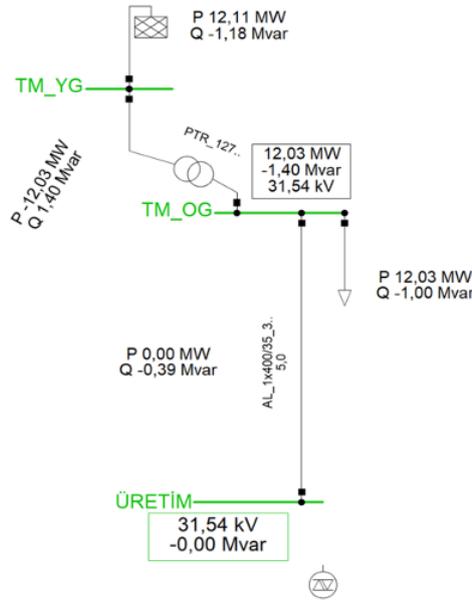


Figure 4
Substation analysis study when the biogas production facility is not in operation [19].

commissioned at the substation. When the biogas production plant comes into operation, according to the analysis results, it is understood that 2,09 MW active and 1,33 MVAR capacitive reactive power is drawn in the transmission transformer (Figure 5). When the reactive power ratio is calculated according to Equation 2, it is seen that the reactive power ratio is 64% when the generation plant comes into operation. This calculated value is above the 15% limit value within the scope of the regulation.

$$\text{Reactive Power Ratio} = \text{tg}\delta = \frac{Q}{P} = \frac{1,33}{2,09} = 0,64V(x) = x * (l - 2 * x) * (w - 2 * x) \quad (2)$$

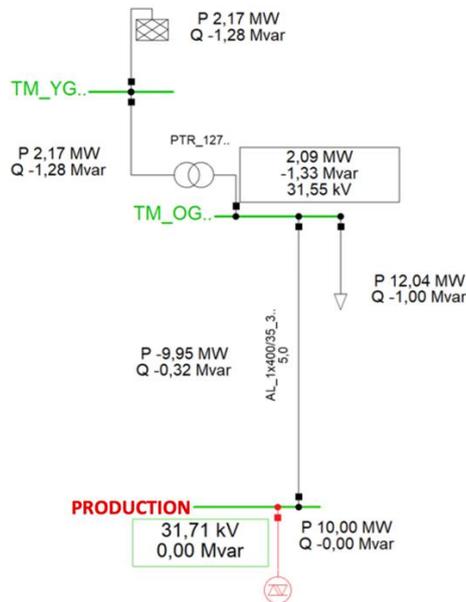


Figure 5
Substation analysis study while the biogas production facility is in operation [19].

Simulation 3: Determination of Compensation Investment Needs

When the load profile data was analyzed based on one-year data after the biogas production plant was put into operation (Figure 6), it was found that a 1,32 MVAR reactor investment was required to keep the capacitive reactive ratio within 15% limits.

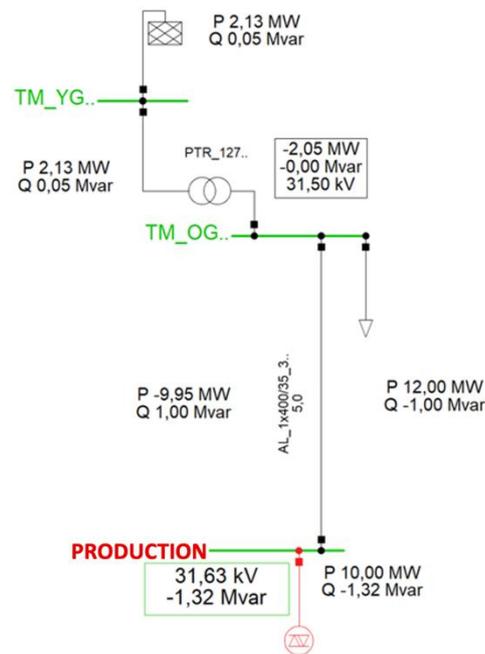


Figure 6
 Determination of compensation investment need while the biogas production facility is in operation [19].

For the three simulation studies conducted above, the net active power drawn from the substations, the reactive power found in the substations, and the reactive power ratio in the grid are shown in Table 1.

Table 1
 Summary information of simulation studies.

Simulation	Explanation	Net Active Power in Transformer (MW)	Net Reactive Power in Transformer (MVar)	Reactive Power Ratio
Simulation 1	Current Situation	12,03	1,4	0,11
Simulation 2	Commissioning of the biogas production plant	2,09	1,33	0,64
Simulation 3	Determination of compensation investment needs	2,05	0	0

Implementation of Pilot Application

After the preparations for the pilot application were completed, the pilot application was carried out between 16.01.2024 at 19:00 and 17.01.2024 at 02:00. Since there was no production after sunset on 15.01.2024 in the transformer, whose active power curve was the same the day before and the day after, it was observed that the capacitive reactive increase in the grid originating from the production plant conductor. After sunset at 19.00 on 16.01.2024, reactive power support started to be received from the SPP inverter. The support process ended at 02.00 on 17.01.2024. As soon as the support process was completed, the value that appeared inductive in the load profile suddenly turned out to be capacitive. In the pilot application, a total of 2,4 MVar inductive reactive support was provided to the system, 400 kVar from each of the 6 inverters in the solar power plant site.

Figure 7 shows the measured instantaneous power values of the transmission transformer. When Figure 7 is examined, active power decreases from 7,6 MW to 0,2 MW between 19.00 in the evening and 09.00 in the morning, the day before the pilot study. Likewise, in the transmission transformer data, the capacitive reactive power value reaches up to 1,8 MVar. In the evening of the same transmission

transformer, between 19.00 and 02.00, when we receive reactive power support from inverters, the active power value decreases from 7,6 MW to 4,8 MW. However, since we receive reactive power support, the amount of reactive power drawn from the system does not increase in the capacitive direction as it did the previous day, on the contrary, it increases slightly in the reactive direction. Thus, the system, which had 1,8 MVAR capacitive reactive power the day before, goes in the opposite direction, and the transformer is loaded inductively, and approximately 0,4 MVAR inductive reactive power appears in the system. This 6-hour support shows that this support will be sufficient for a 6-month period in which the production-consumption trend of the transmission transformer will not change during the winter period. Finally, when inductive reactive power support from solar inverters is stopped, capacitive power is generated in the system again between 02.00 and 08.00.

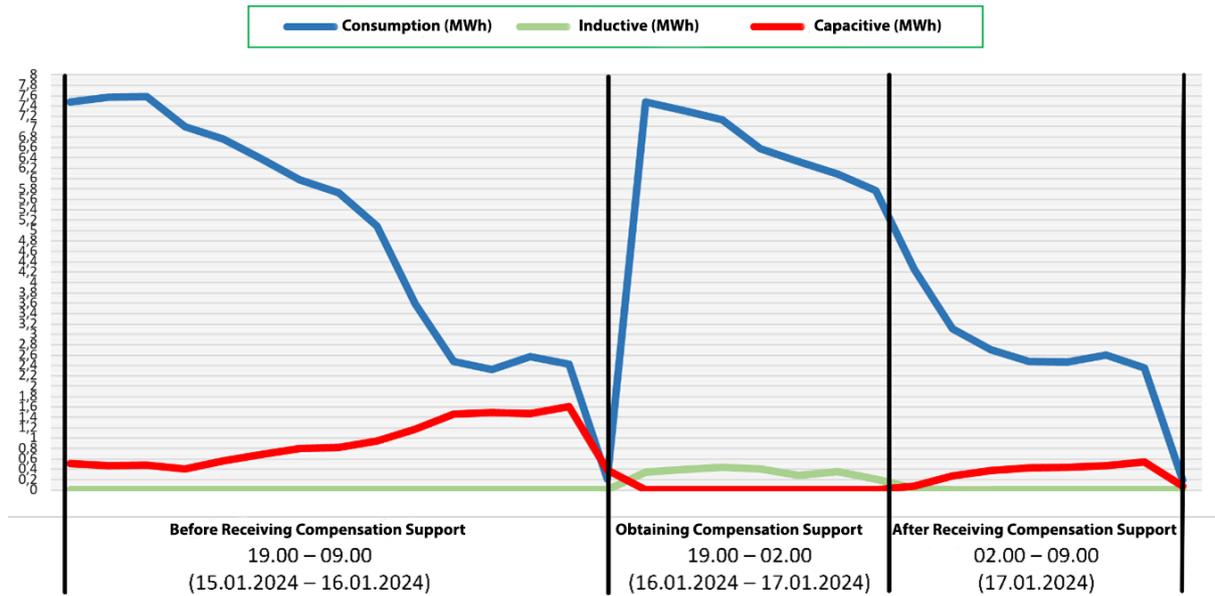


Figure 7
Transmission transformer load profile (Change in Substation Meter Values as a Result of Inductive Reactive Support from Solar Inverter)[19].

In addition, according to the trend graph of an inverter at the time of receiving support, when a command was sent to receive 400 KVAR inductive reactive power support, the inverter responded in a very short time. According to the SCADA screenshot in Figure 8, the inverter provided continuous reactive power support.

Cost Analysis: Meeting the Compensation Needs of Electricity Distribution Region in 2023 from Solar Power Plants

As a result of the analysis carried out in the distribution region of electricity distribution company, the compensation needs for the substations from which energy is received were determined. In line with these findings, it was revealed that 16 different substation reactors needed to be invested. Table 2 shows the power and investment costs of 25 reactor investments that need to be made for these 16 different substations. A total of 65,6 MVAR reactor power and a cost of \$1.890.223 is needed for 25 reactor investments. The solar power plants located on the feeders connected to the substations in this region have a total production capacity of 1054,73 MW. In addition, the required reactor power value for each

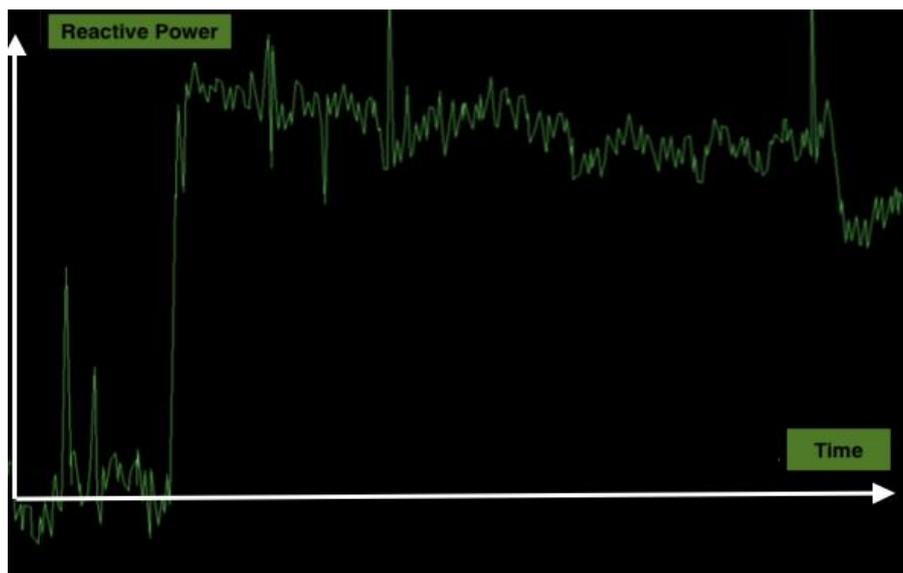


Figure 8
Trend of receiving reactive power support of an inverter.

feeder is less than the reactor power we can get from the solar power plant connected to the relevant feeder. Therefore, all of the reactor power required for each transformer can be provided by solar power plants. In this case, the \$1.9 million cost benefit required for the reactor investment can be achieved when reactive support is received from the solar power plant instead of the compensation systems that need to be installed only for 2023.

Table 2
Compensation investment needs for the electricity distribution region in 2023 and installed plants connected to relevant transformers.

Substation	Shunt Reactor (MVar)	Investment Cost	Solar Power Plant Installed Power Connected to The Electricity Distribution Grid (MW)
TM 1- TRA	2,4	\$ 75.351	
TM 1- TRB	1,8	\$ 69.527	15,34
TM 2- TRA	3,6	\$ 69.368	
TM 2- TRA	2,4	\$ 72.158	55,38
TM 2- TRB	1,8	\$ 69.527	
TM 3- TRA	3,6	\$ 98.672	89,78
TM 4- TRA	1,8	\$ 69.527	53,11
TM 5- TRA	2,4	\$ 75.351	61,7
TM 6- TRA	1,8	\$ 71.742	
TM 6- TRB	1,8	\$ 71.742	88,79
TM 7- TRA	3,6	\$ 88.302	
TM 7- TRB	2,4	\$ 75.351	67,34
TM 8- TRA	2,4	\$ 69.731	
TM 8- TRB	2,4	\$ 75.351	75,84
TM 9- TRA	2,4	\$ 51.451	
TM 9- TRB	2,4	\$ 75.351	134,33
TM 10- TRA	3,6	\$ 51.451	
TM 10- TRB	2,4	\$ 75.351	73,15
TM 11- TRA	5	\$ 105.692	38,95
TM 12- TRA	2,4	\$ 75.799	59,05
TM 13- TRA	2,4	\$ 76.174	101,85
TM 14- TRA	2,4	\$ 93.268	
TM 14- TRB	2,4	\$ 75.351	79,5
TM 15- TRA	2,4	\$ 64.103	14,35
TM 16- TRA	3,6	\$ 94.535	46,3
TOTAL	65,6	\$ 1.890.223	1054,73

Technical Loss Analysis: Meeting the Compensation Need of Electricity Distribution Region in 2023 from Solar Power Plants Technical Loss Analysis

Within the scope of this study, the effects of receiving reactive power support from solar power plants and making reactor investments on the grid were examined and compared. Using the meter data on the inlet side of the reactor connected to the grid and the index values in the meter data at the reactor exit, the technical loss rate was calculated as 5,35%. Likewise, when reactive support is received from the solar power inverter, the technical loss rate calculated using the values taken while the inverter is on and the values taken when the inverter is off, in line with the values taken from the technical quality recorder data, is 2,65%.

The average consumptions for these two applications, when 2400 kVAr reactive power support is received from both the reactor and the solar power inverter, are as in Table 3. For both supports, according to 8760 hours of data, a technical loss cost of approximately 8,5 million TL arises (calculation was made by taking 2023 electricity generation company and market average: 1097 ₺/MWh).

Table 3
Lost Energy Cost in 2023.

Active Power (MW)	Loss Rate Difference Between Reactor and Solar Inverter	Lost Power (MW)	8760 Hours of Lost Energy (MWh)	Lost Energy Cost in 2023 (₺)
35,28	2,50%	0,882	7726,32	₺8.475.773

According to this technical loss study conducted for only a single transmission transformer, a total technical loss cost of 8,5 million ₺ occurs in a year. When this is done in the compensation systems connected to all transformers in the substations in our country, the costs resulting from technical losses will be much higher.

DISCUSSION AND CONCLUSIONS

The problem caused by the increase in capacitive reactivity as a result of the introduction of renewable energy sources was solved by obtaining inductive support from a solar power plant connected to the same substation. As can be seen from the performance expected from SPPs, reactive power support is a well-known method to ensure voltage regulation and most of the new generation vehicles based on power electronics are well suited for this purpose. For this reason, it has been proven to benefit from the reactive capacities of solar power inverters as well as reactive power compensation investments to ensure reactive power flow limits. Electricity distribution companies make compensation investments in order to avoid substation-based reactive penalties. These investments are made not on a feeder basis, but only to keep the substation's reactive power within its limits. For example, a substation needs inductive reactive power support. If this need is supplied by an inductively loaded feeder, it will cause an increase in technical loss. The substation may be kept within the limit values, but feeder-based losses will increase. However, if this is done by taking solar power plants, technical losses can be further reduced by providing both transformer-based and feeder-based compensation.

With the reactive power support that can be provided from renewable energy sources, especially inverter-controlled facilities, which have recently increased in electricity distribution company, the grid voltage will be effectively controlled in the +/- direction, and the compensation investments made every year will be significantly reduced. Operational problems encountered as a result of the increase in distributed generation resources will be reduced and renewable energy integration will increase. In addition, another important result of effectively controlling the voltage profile is that it has been proven that it will enable the optimization of technical losses, and help increase grid efficiency, according to the comparison of reactive support received from the reactor and solar power inverter. Finally, in the

current situation, compensation facilities are connected to a feeder of the substation. Electricity distribution companies only make compensation investments to avoid reactive penalties. For example, let's assume that a substation needs an inductive reagent. In this case, inductive support is received from the reactor connected to a feeder. But perhaps the feeder connected to the reactor is inductively loaded. In order to remain at the reactive limit value, the substation receives inductive support from the inductively loaded feeder, causing technical losses to increase even more. When reactive support from generation plants connected to the distribution grid becomes widespread, these will be analyzed on a feeder basis, so the substation will remain within the reactive limit range, and technical loss optimization will be made by receiving support from the relevant feeder according to the reactive needs of the substation feeder outputs.

Ethical Statement

This study was produced from the master's thesis titled "Providing Reactive Power Support From Solar Power Source In Electricity Distribution Grid" submitted on 04.07.2024 under the supervision of Sabri Altunkaya.

Ethics Committee Approval

This study does not require any ethics committee approval.

Author Contributions

Research Design (CRediT 1) : H.K. (%60) – S.A. (%40)

Data Collection (CRediT 2) : H.K. (%100)

Research - Data Analysis - Validation (CRediT 3-4-6-11) : H.K. (%80) – S.A. (%20)

Writing the Article (CRediT 12-13) : S.A. (%100)

Revision and Improvement of the Text (CRediT 14) : S.A. (%100)

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Conflict of Interest

The authors have no conflicts of interest to disclose for this study.

Sustainable Development Goals (SDG)

Sustainable Development Goals: 7 Affordable and clean energy.

REFERENCES

- [1] S. Sreekumar, D.S. Kumar and J.S. Savier, A case study on self healing of smart grid with islanding and inverter volt–VAr function, *IEEE Transactions on Industry Applications*. 56 (2020), 5408-5416. doi:10.1109/TIA.2020.3011664
- [2] B.E. Tankut. Voltage Regulation for Grid Connected Photovoltaic Systems using Reactive Power, Yüksek Lisans Tezi, Hasan Kalyoncu Üniversitesi Fen Bilimleri Enstitüsü, Elektronik ve Bilgisayar Mühendisliği Ana Bilim Dalı, Gaziantep, 2019
- [3] T.A. Boghdady and Y.A. Mohamed, Reactive power compensation using STATCOM in a PV grid connected system with a modified MPPT method, *Ain Shams Engineering Journal*. 14 (2023), 102060. doi:10.1016/j.asej.2022.102060
- [4] A.A. Suryawanshi and A. Tapde, Maximizing solar power output with pv-statcom for reactive power compensation in on-grid systems, *International Journal of Intelligent Systems and Applications in Engineering*. 12 (2024), 3382-3387.
- [5] P. Jahangiri and D.C. Aliprantis, Distributed Volt/VAr control by PV inverters, *IEEE Transactions on Power Systems*. 28 (2013), 3429-3439. doi:10.1109/TPWRS.2013.2256375
- [6] M.S.I. Tarek, A. Siam, M. Zia and M.M. Rahman. A Novel Five-Level Inverter Topology with Reactive Power Control for Grid-Connected PV System. In: 2018 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE). Kajang, Malaysia, 2018. doi:10.1109/ICSGCE.2018.8556812
- [7] W. Zhong, G. Tzounas and F. Milano, Improving the power system dynamic response through a combined voltage-frequency control of distributed energy resources, *IEEE Transactions on Power Systems*. 37 (2022), 4375-4384. doi:10.1109/TPWRS.2022.3148243
- [8] G. Lalor, A. Mullane and M.O. Malley, Frequency control and wind turbine technologies, *IEEE Transactions on Power Systems*. 20 (2005), 1905-1913. doi:10.1109/TPWRS.2005.857393
- [9] A.J. Lamadrid and T. Mount, Ancillary services in systems with high penetrations of renewable energy sources, the case of ramping, *Energy Economics*. 34 (2012), 1959-1971. doi:10.1016/j.eneco.2012.08.011
- [10] N.K. Roy, H.R. Pota and M.J. Hossain, Reactive power management of distribution networks with wind generation for improving voltage stability, *Renewable Energy*. 58 (2013), 85-94. doi:10.1016/j.renene.2013.02.030
- [11] A. Chatterjee, K. Mohanty, V.S. Kommukuri and K. Thakre, Design and experimental investigation of digital model predictive current controller for single phase grid integrated photovoltaic systems. *Renewable Energy*. 108 (2017), 438-448. doi:10.1016/j.renene.2017.02.057
- [12] R. Krishan, S.K. Singh, S. Patnaik, S. Verma. Reactive Power Control Strategies for Solar Inverters to Increase the Penetration Level of RE in Power Grid. In: 2nd International Conference on Large-Scale Grid Integration of Renewable Energy in India. New Delhi, India, 2019.
- [13] K. Tharuka Lulbadda and U. Hemapala, Use of solar PV inverters during night-time for voltage regulation and stability of the utility grid, *Clean Energy*. 6 (2022), 646-658. doi:10.1093/ce/zkac042
- [14] A.M. Howlader, S. Sadoyama, L.R. Roose and S. Sepasi, Distributed voltage regulation using Volt-Var controls of a smart PV inverter in a smart grid: An experimental study, *Renewable Energy*. 127 (2018), 145-157. doi:10.1016/j.renene.2018.04.058
- [15] P. Kayal and C.K. Chanda, Strategic approach for reinforcement of intermittent renewable energy sources and capacitor bank for sustainable electric power distribution system, *International Journal of Electrical Power & Energy Systems*. 83 (2016), 335-351.

doi:10.1016/j.ijepes.2016.04.029

- [16] A. Joseph, K. Smedley and S. Mehraeen, Secure power distribution against reactive power control malfunction in DER units, *IEEE Transactions on Power Delivery*. 36 (2021), 1552-1561. doi:10.1109/TPWRD.2020.3011376
- [17] F. Bernáth and P. Mastný, Power factor compensation of photovoltaic power plant, *Electroscope* 5 (2012)
- [18] Anonim, Elektrik Şebeke Yönetmeliği, <https://www.epdk.gov.tr/Detay/Icerik/3-6730/elektrik--sebeke-> (accessed 12 January 2024).
- [19] H. Koroğlu. Elektrik Dağıtım Şebekesinde Güneş Enerji Santralinden Reaktif Güç Desteği Sağlanması, Yüksek Lisans Tezi, Necmettin Erbakan Üniversitesi Fen Bilimleri Enstitüsü, Elektrik Elektronik Mühendisliği Ana Bilim Dalı, Konya, 2024
- [20] M. Flota-Bañuelos, M. Espinosa-Trujillo, J. Cruz-Chan and T. Kamal, Experimental study of an inverter control for reactive power compensation in a grid-connected solar photovoltaic system using sliding mode control, *Energies*. 16 (2023), 853. doi:10.3390/en16020853
- [21] V. Kumar and M. Singh, Reactive power compensation using derated power generation mode of modified P&O algorithm in grid-interfaced PV system, *Renewable Energy*. 178 (2021), 108-117.
- [22] A. Dhaneria. Grid Connected PV System with Reactive Power Compensation for the Grid. In: 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT). Washington, DC, USA, 2020. doi: 10.1109/ISGT45199.2020.9087728