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PERFORMANCE IMPROVEMENT IN A 1 MW GRID-CONNECTED PV POWER PLANT INSTALLED IN YATAĞAN-MUĞLA TURKEY VIA STATCOM ON MATLAB-Simulink PORTAL

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Keywords
*MATLAB-Simulink, PV Systems, STATCOM, Reactive Power Compensation, Power Plant***.**

Abstract
A grid-connected power system's performance depends on the produced energy's power quality and power coefficient. The higher the power quality of the energy transferred to the grid, the more critical it is for power plants, energy distribution systems and end-users. This study investigated the optimisation possibilities obtained by applying STATCOM (Static VAR Compensation) for a 1 MW PV-based Solar Power Plant (PV-SPP) in the Muğla-Türkiye province. First, the data of components such as the inverter and PV panel that make up the plant were obtained, and the raw MATLAB-Simulink modelling of the plant was carried out. System performance outputs were obtained by adding STATCOM modelling to the obtained modelling. The scientific results of the optimisation would be obtained if this technique was applied to the existing power plant. Since STATCOM also performs the RPC (Reactive Power Compensation) process, it is an up-to-date and effective technique that improves system energy power quality. According to the simulation results, this system with STATCOM draws 24,043% and 11,671% less reactive power and current than the non-STATCOM system.

YATAĞAN-MUĞLA TÜRKİYE' DE KURULU OLAN 1 MW ŞEBEKE BAĞLANTILI BİR PV GÜÇ SANTRALİNDE MATLAB-SIMULINK PORTALINDA STATCOM YOLUYLA PERFORMANS İYİLEŞTİRİLMESİ

Anahtar Kelimeler
MATLAB-Simulink, PV-GES, STATCOM, Reaktif Güç Kompanzasyonu, PV Sistemler.

Öz
Şebekeye bağlı bir güç sisteminin performansı, üretilen enerjinin güç kalitesine ve güç katsayısına bağlıdır. Şebekeye aktarılan enerjinin güç kalitesi ne kadar yüksekse santraller, enerji dağıtım sistemleri ve son kullanıcılar için o kadar kritiktir. Bu çalışma, Muğla-Türkiye ilinde bulunan 1 MW'lık bir PV tabanlı Güneş Enerjisi Santrali (PV-GES) için STATCOM (Statik VAR Kompanzasyonu) uygulanarak elde edilen optimizasyon olanaklarını araştırmıştır. Öncelikle tesisi oluşturan inverter ve PV panel gibi bileşenlerin verileri elde edilmiş ve tesisin ham MATLAB-Simulink modellemesi gerçekleştirilmiştir. Elde edilen modellemeye STATCOM modellemesi eklenerek sistem performans çıktıları elde edilmiştir. Optimizasyonun bilimsel sonuçları, bu tekniğin mevcut santrale uygulanması durumunda elde edilecektir. STATCOM, RPC (Reaktif Güç Kompanzasyonu) işlemini de içerdiğinden, sistem enerji güç kalitesini iyileştiren güncel ve etkili bir tekniktir. Simülasyon sonuçlarına göre, STATCOM uygulanmış sistem, önceki sisteme göre %24,043 daha az reaktif güç ve %11,671 daha az akım çekmektedir.

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Highlights

- In the study, the improvement in the quality of the energy produced in a PV system was simulated.
- The work carried out is an efficiency-enhancing method for grid-connected PV plants at present.
- STATCOM technique brings advantages not only for PV power plants but also for end users.

Graphical Abstract

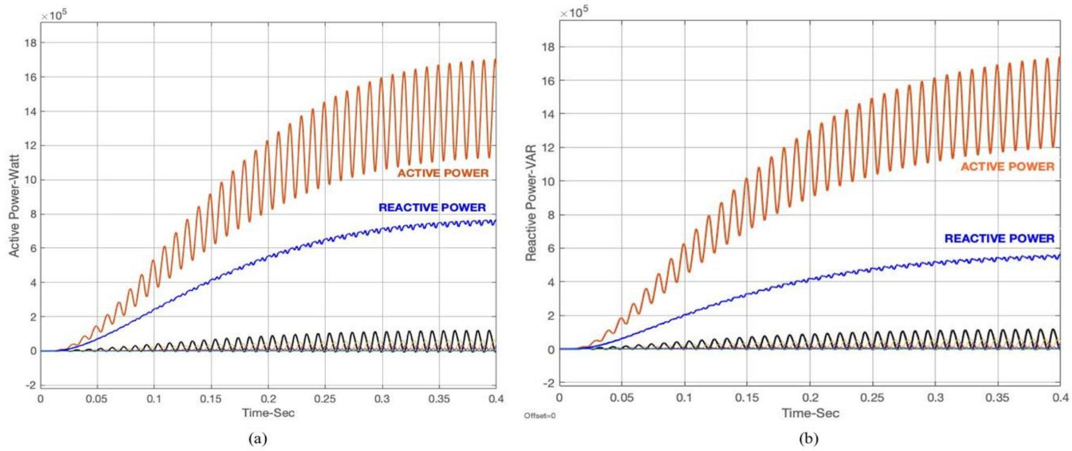

Figure. Active/ reactive power waveform (a) without and (b) with STATCOM

Purpose and Scope

The main purpose of this study is to develop a performance-enhancing technique for transferring the energy produced in a grid-connected PV system to end users in a quality way through the STATCOM application.

Design/methodology/approach

MATLAB-Simulink, which is an effective simulation-modelling tool to achieve the purpose of the study. used. While developing the basic mathematical model on which the method is based, the structural single-line diagram

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of a PV power plant and the connected energy transmission line is based. The evaluation was made over AC power equations and vector diagrams, and the model was completed with STATCOM equations.

Findings

From the point reached with the survey, improvements and improvements have been achieved in the parameters that determine the power quality of the energy obtained from the power system.

Originality

In general, studies on STATCOM applications are handled on transmission and distribution systems, but a technique that will not only improve the quality of energy produced in a grid-connected PV plant but also bring improvement in terms of energy transmission and distribution lines is discussed in this study. The study aims to help researchers who carry out optimization activities in power plants and energy systems.

1. Introduction

Global warming threatens the sensitive ecosystems of our world and quickly destroys or damages many natural life forms. One of the most fundamental factors that cause global warming is the fossil fuel-based energy conversion processes that have emerged globally, causing the assumption of greenhouse gases. About 80% of the energy consumed to date is derived from non-renewable energy sources, e.g., fossil fuels (Tobnaghi, 2016). Greenhouse gases and pollutants increase when fossil fuels are converted into electricity or heat. Therefore, the atmosphere is damaged. This situation emerges as the most decisive factor affecting the ecosystem negatively. Due to the gradual depletion of fossil fuels, the need for electrical energy has increased globally. Renewable energy technology has emerged as an effective and appropriate solution to the energy crisis due to its environmentally friendly, green, and pollution-free features, due to both the global pollution and negative environmental impact caused by the energy conversion processes in fossil fuels and the decrease in fossil fuel reserves. PV energy has started to be preferred more among other energy sources due to its inexhaustibility in terms of its energy source and its positive environmental effects. (Priyadarshi etc., 2017).
Photovoltaic energy production is widespread as a clean energy source globally, and environmental factors such as working in various environments and solar radiation are critical working parameters for PV systems. Module temperature seriously affects the production performance of systems (Nishioka etc., 2003).

A PV system can operate in different solar radiation and temperature conditions, and its operating performance is directly affected by these factors. (Kameda etc, 1996; Sewang etc. 1994; Hishikawa etc., 1994.). Suppose the PV system is designed as a power plant; power quality, energy transmission efficiency, and the parameters given above affect the total system performance. Some up-to-date techniques have been developed as performance-enhancing optimisation methods for these designs. In general, these techniques are compensation and STATCOM applications, including the RPC process. Unlike manual-mechanical controlled transmission systems, facts devices used in power systems can overcome instantaneous electrical stresses. Industrial development increases the need and demand for such devices in power plants and transmission systems. As energy and power transfer becomes widespread, the use of power electronic elements for system stability and reliability increases, for this reason, generally energy control in PV systems is provided by power electronic converters (İşen etc., 2021).

When examined on the scale of Turkey, the biggest problem of distribution systems is the inability to provide uninterrupted energy to the consumer (Güner etc., 2022). PV-SPPs with STATCOM application can help to reduce these problems.

Harmonic resonances and reactive transmission problems are the leading factors affecting the power quality of PV-SPPs. Such problems directly affect the generation and transmission capacity of the power system (Guo etc., 2020). Studies and developments in this area have gained much more critical attention in increasing the efficiency of compensators' grid and power systems (Dixon etc., 2005). Utilising this study, in the case of applying STATCOM to a PV-SPP installed in the MUĞLA-Yatağan locality, the arrangements obtained in the current-voltage characteristics have been reached. A decrease in current and reactive power values has been achieved, increasing system efficiency.

1.1. STATCOM

The RPC process is defined as controlling the active and reactive power values by interfering with the system's power factor. This way, it is carried out to increase the performance of ac power systems. Reactive power consumes transmission capacity and reduces system efficiency significantly, increasing energy generation and transmission costs. The RPC process generally takes place in two dimensions: load compensation and voltage regulation. With the control of the system power factor, the load compensation is carried out, and the system voltage and current regulation are also realised similarly. The control of harmonics created by large non-linear industrial loads is an important and necessary process. (Wanner etc., 2022; Bonnard 1985).

One of the critical applications that provide stability and dynamic character regarding power transmission, which is one of the essential processes of AC transmission systems, is; STATCOM. A STATCOM consists of complex control systems and IGBTs to dynamically control reactive power, continuously regulating voltage on the transmission line. A STATCOM generally consists of an IGBT voltage-source converter, series-connected phase reactors, and a step-up power transformer.
Key advantages of this process;

- Boost transmission network stability and reliability
- Connect into transmission systems between generation and end-users
- Providing reactive power to electric transmission systems

STATCOM devices occupy an important position in terms of new-generation power systems. A STATCOM design is generally implemented as a DC-AC voltage converter developed with a capacitor unit. Together with a transformer, this unit performs control as a Synchronous Voltage Source (SVS) on a dynamic basis. In the STATCOM way and the phase controls of the voltages, the capacitive-inductive current control in the line is realised more quickly (Qingguang etc., 2004). Each STATCOM unit can be considered a DC-AC voltage source. In these systems, capacitor groups are used as the main energy source. Using step-up transformers, the energy obtained from these units is increased to the required voltage values for transmission lines and end users and transferred to the network. In this respect, STATCOM systems also have an SVS feature. STATCOM controls the voltage at the line terminal by controlling the amount of reactive power the power system needs or needs to transfer according to its demand. RPC is performed via the VSC connected to the secondary side of a step-up transformer given to the system or the amount of active power it receives. On the other hand, in relation to other previous studies in this field; some methods and algorithms suggested in parallel with the theory of the study are given in Table 1 (Montoya etc.2019; Liu etc., 2020; Osman etc., 2004).

Table 1. Proposed methods associated with the study

SYMBOL	YEARS	AUTHORS	ALGORITHM
GA	2019	Francisco G. Montoya	Geometric algebra
NTDS	2020	Muyang Liu, etc.	Neutral Time-Delay System
PSO	2020	Muyang Liu, etc.	Particle swarm optimisation
DWT	2004	A. H. Osman and O. P. Malik	The discrete wavelet transforms

2. Material and Method

The PV power plant, the basis for the operation, consists of 22 serials-connected BOVIET branded panels with the product code SOLAR-BVM6610P-270, 16 lines comprised of 12, 22 serially connected panels 1 line composed of 8 parallel strings. It consists of a total of 17 inverter-connected lines (Figure 1,2). In addition, the technical specifications of the inverter and PV panels, which form the basis of the PV-SPP system, are given in Tables 2 and 3.

Figure 1. Reviewed PV-S

Table 2. PV panels features of the system

Number of Cells	60	**V_{OC}**	38,3 V
STC Power	270 W	**NOTC**	45 °C
I_{MP}	8,71 A	**Max. Syst. Voltage**	1000 V
V_{MP}	31 V	**Number of Panels**	4400
I_{SC}	9,16 A		

Table 3 Inverter Features of the System

DC Side-Voltage	720 V	**Total Output Power**	1,1 MW
DC Side-Power	61,8 kW	**Total Output Current**	1,6 kA
AC Grid Voltage	380-570 V	**Total Output Voltage**	682 V
AC Side-Power	71 kW		
Number of Inv.	17		

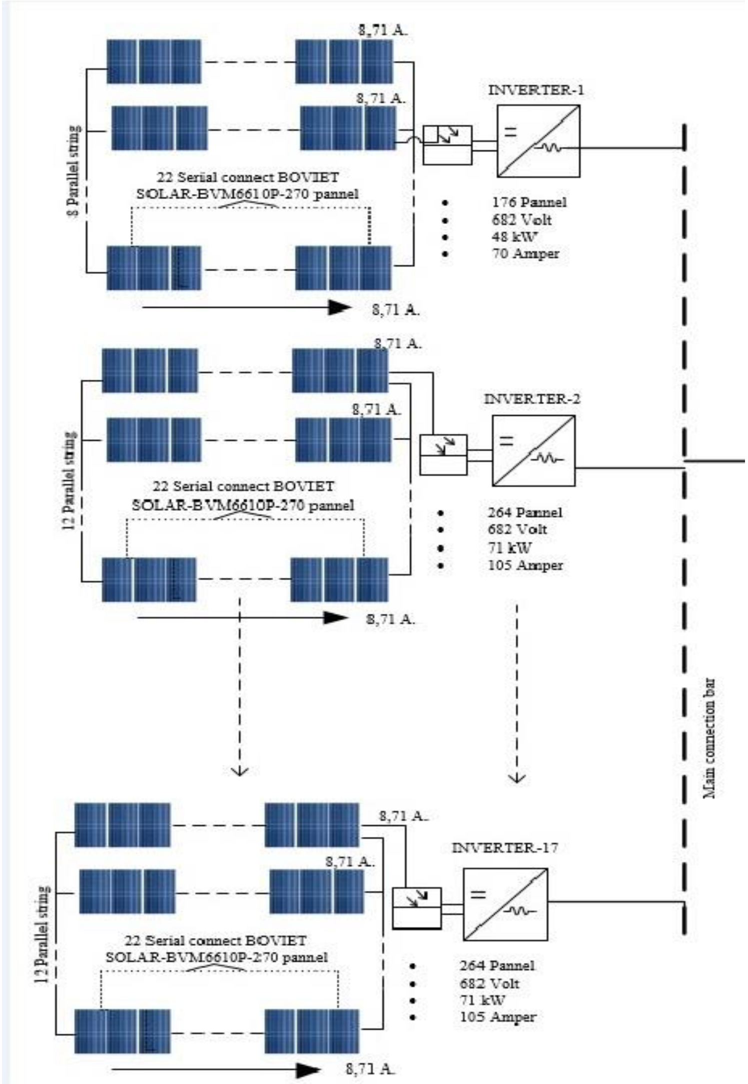

Figure 2. Single-line diagram of PV Strings

2.1. Simulink Modeling of the Studied System

Simulink modelling of the considered system was created based on mathematical models at this study stage. To design Simulink modelling more compact, 16 of 17 sequences with the same parameter values were brought together under a sub-mask. The high-power quality of PV-SPP will increase the efficiency of transmission lines and power systems. It will also get an overall economic benefit by reducing the power values of the components used in transmission lines and production systems. On the other hand, one of the up-to-date and effective techniques to improve power quality in power distribution systems and transmission lines is the STATCOM application. With this application, the distortions (for example, harmonics) occurring in the available waveforms of energy parameters, such as current and voltage transferred to end-users, are brought to an arrangement. At the same time, an increase in the power quality of the energy produced is achieved by performing RPC. The Simulink modelling of this arrangement is given in Every STATCOM module consisting of six IGBT sub-module, a DC capacitor and a control unit. At the same time, Simulink modelling of transmission-distribution grid sections containing distribution lines and end-users was performed and gathered under the sub-system (Figure 3). The single-line diagram, which is the basis for modelling the optimised PV-SPP system, is given in Figure 4.

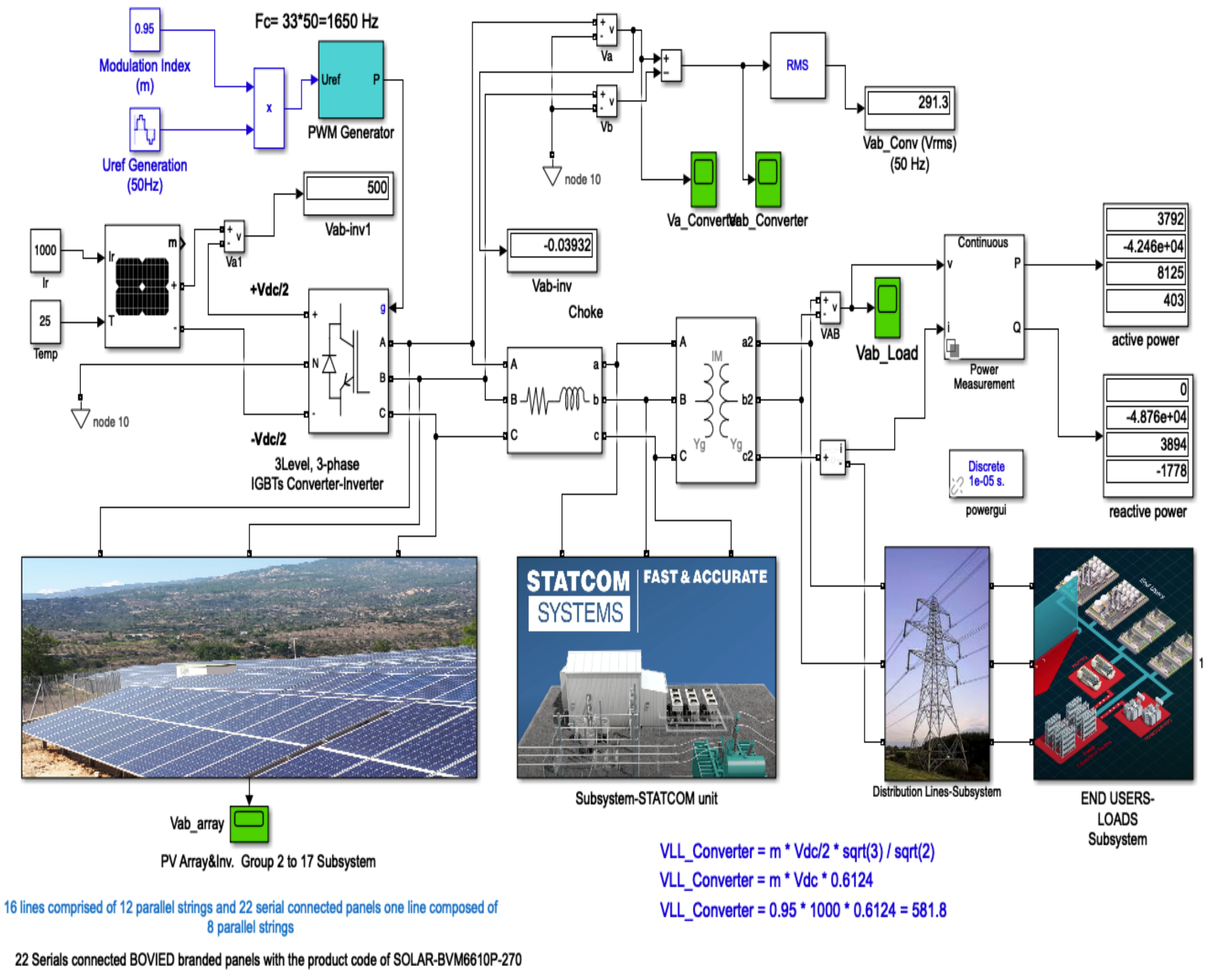

Figure 3. MATLAB-Simulink modelling of the optimised system

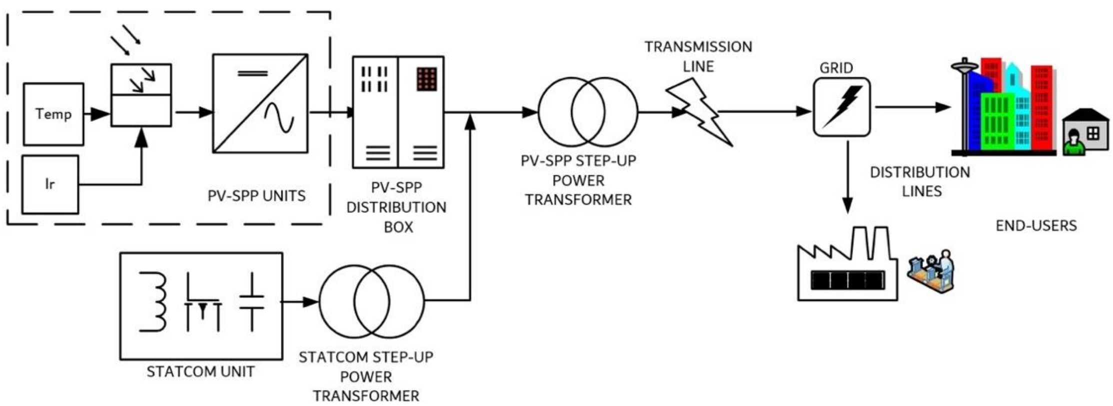

Figure 4. Single-line diagram of optimised PV-SPP

2.2. Mathematical Model

The phase angle between current and voltage in the RPC process is also reduced, reducing total apparent power. Vector diagrams of this process can be seen in figure 5.

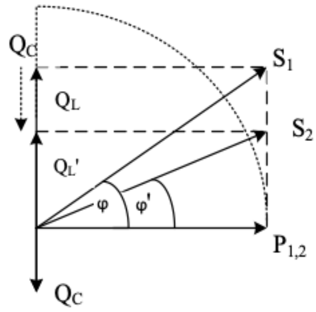

Figure 5. AC Powers vector diagram pre & post RPC

Parameter values in Figure 5 are calculated with the equations given below;

$$S_1 = \sqrt{(P_1^2 + Q_L^2)} \quad (1)$$

$$S_2 = \sqrt{(P_2^2 + Q_{L'}^2)} \quad (2)$$

$$P_1 = \sqrt{3}.u.i.cos\ \varphi \quad (3)$$

$$P_2 = \sqrt{3}.u.i'.cos\ \varphi' \quad (4)$$

$$Q_C = P_{1,2}.(tg\ \varphi - tg\ \varphi') \quad (5)$$

The meanings of the symbols in the formulas are as follows; P_1, P_2; Active power post-and-pre-RPC, ΔQ_C; Capacitor capacity for compensation process, Q_L, Q_L'; reactive power without and with RPC, S_1, S_2; apparent power without and with RPC, $i - i'$; current post-and-pre-RPC, $\varphi - \varphi'$; phase angle post-and-pre-RPC, u; system voltage (Kalay etc., 2021).

The phase difference between the busbar voltage and the converter's output voltage. It is written as Where Vo is the busbar voltage, V is the converter's output voltage, X is the link transformer's voltage, leakage reactance, and δ is the connected state of STATCOM (Çöteli, 2007) (Figure 6). Δ is the angle of V concerning V_0. Since δ is very small, if we set δ=0, if V_0 is higher than V, Q flows from V_0 to V (i.e., STATCOM absorbs reactive power). Conversely, if V_0 is lower than V, Q flows from V to V_0 (i.e., STATCOM is generating reactive power), (Wen-Hao etc., 2010).

$$P = \frac{V.V_0}{X} \sin \delta \quad (5)$$

$$Q = \frac{V_0}{X}(V_0 - V.\cos\ \delta) \quad (6)$$

$$P = 0;$$
$$Q = V_0\ \frac{V_0 - V}{X} \quad (7)$$

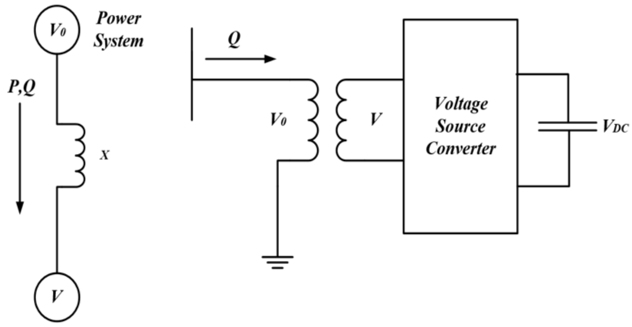

Figure 6. Operating Principle of the STATCOM.

3. Simulation Results

This section analyses the performance parameters obtained before and after the STATCOM simulation. First, the characteristic curves of the PV power system, which are essential to analyse the system as an energy source, are obtained. Performance simulations were carried out in two different situations for the PV-SPP, each sub-array consisting of 22 series-connected PV panels with 12 parallel strings. At first, current and power values are under three different radiation values. Accordingly, 1 kW/m2 value PV-SPP produces the highest power and current values. The data and graphics of this analysis are given in Figures 7-a, b and Table 4.

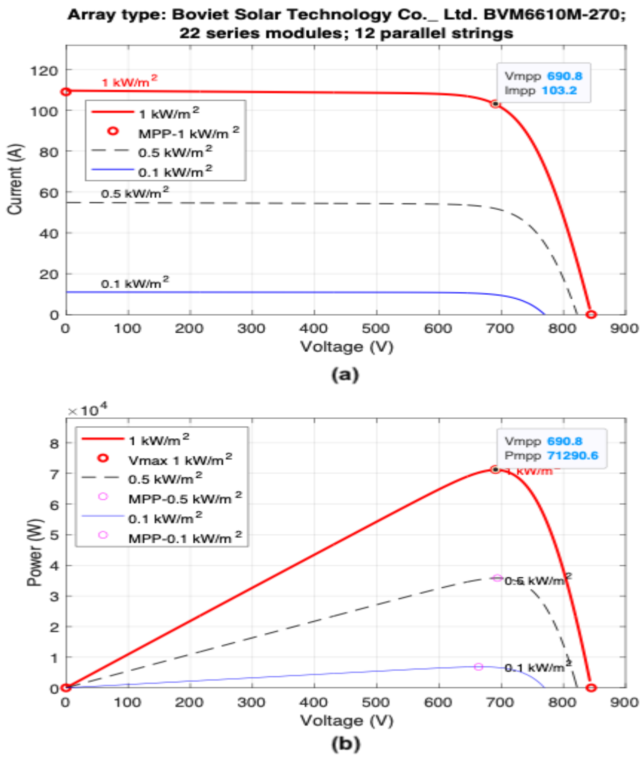

Figure 7. Current-voltage (a), power-voltage(b) graphs under different irradiance condition

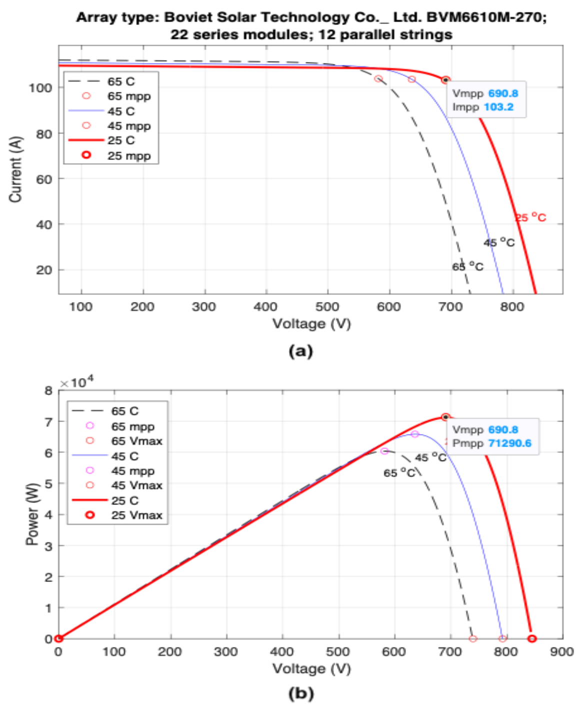

Figure 8. Current-voltage (a) power-voltage (b) graphs under different temperature conditions

This time, the exact process was carried out in varying temperature conditions. Figures 8-a, b and Table 4 show performance graphics and value outputs for different operating temperatures. According to this simulation result, with its 25 °C operational performance, PV-SPP strings produce the most effective operating current, voltage and power.

The optimisation realised in the system is concretely demonstrated. The current, voltage, active and reactive power characteristics that emerge from transferring the system to the load are handled before and after the STATCOM process. For example, although the AC voltage transferred from the system experienced some distortions (harmonics, flickers, etc.) during its transfer to the load, it turned into a voltage characteristic with a smoother waveform after STATCOM (Figure 9,10). After the voltage analysis, the PV-SPP transfers the current under load supply conditions; likewise, analysed under STATCOM pre-and post-conditions. The distortions in the current waveform are transformed to the approximated pure-sine format when post-STATCOM. This situation is seen in Figures 11 and 12. As a result of the RPC process, another function of the application, reactive power control, was also carried out. As shown in Table 4 and the current-carrying capacity has been increased with STATCOM applied to the PV-SPP output at operating conditions of 1 kW/m2 and 25 °C, which are the most effective systems input parameters. As a result of RPC, the active power obtained at the output did not change, but a decrease was achieved in the reactive power and total load current (Figure 13). In addition, the current and voltage values, whose waveforms are given in Figures 9-12, were obtained through scopes connected to the PV-SPP step-up transformer output seen in Figure 3.

Table 4. Performance Results for PV String under different conditions.

Temperature (Irradiance 1 kW/m^2)	Voltage V	Current A	Power kW
65 °C	581,455	103,811	60,362
45 °C	635,68	103,515	65,802
25 °C	690,8	103,2	71,291
Irradiance (Temperature 25 °C)	**Voltage V**	**Current A**	**Power kW**
1 kW/m^2	690,8	103,2	71,291
0,5 kW/m^2	693,828	51,08	35,844
0,1 kW/m^2	663,551	9,433	0,687

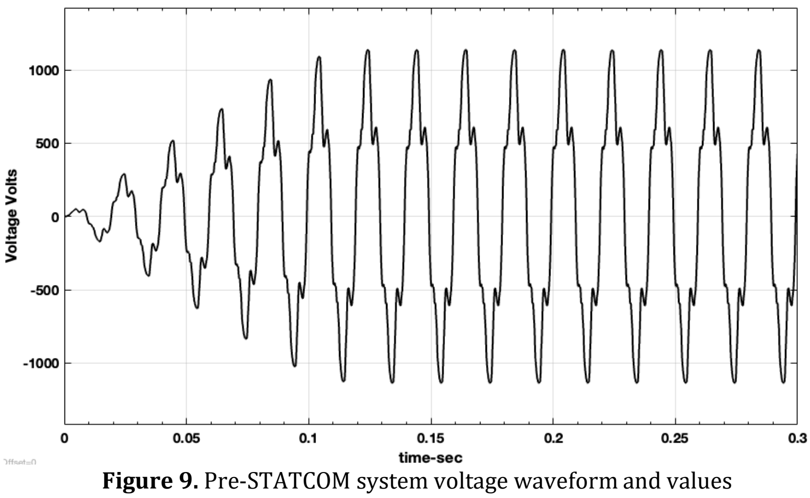

Figure 9. Pre-STATCOM system voltage waveform and values

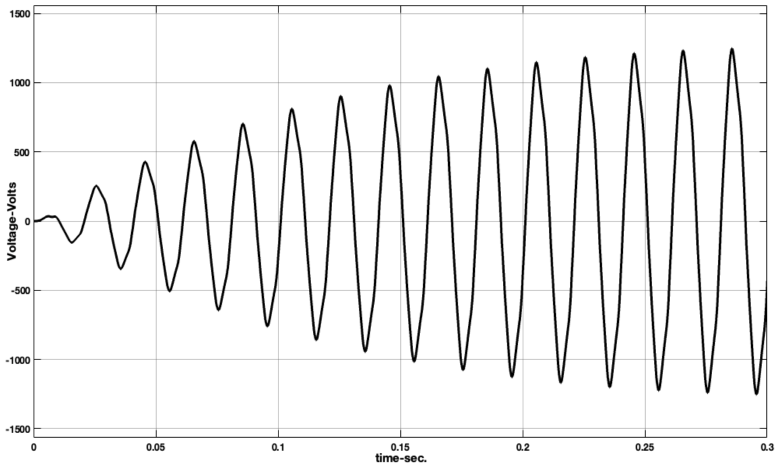

Figure 10. After STATCOM system voltage waveform

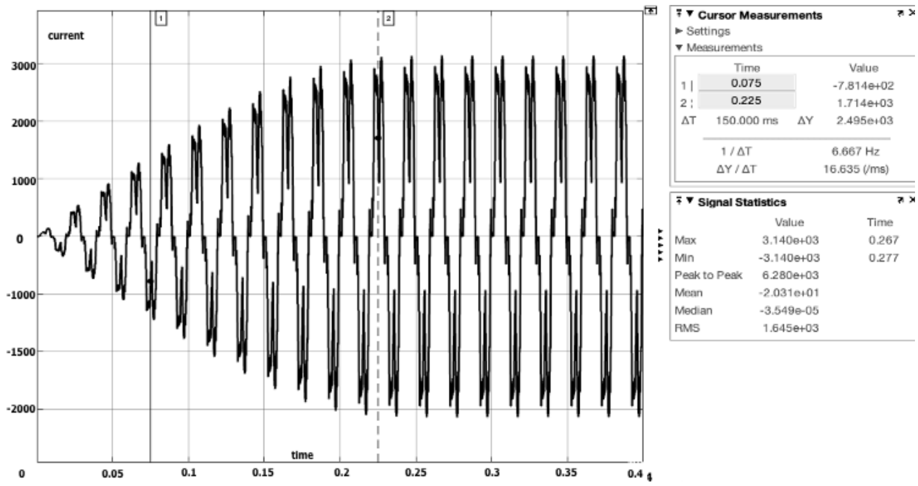

Figure 11. Pre-STATCOM system current waveform

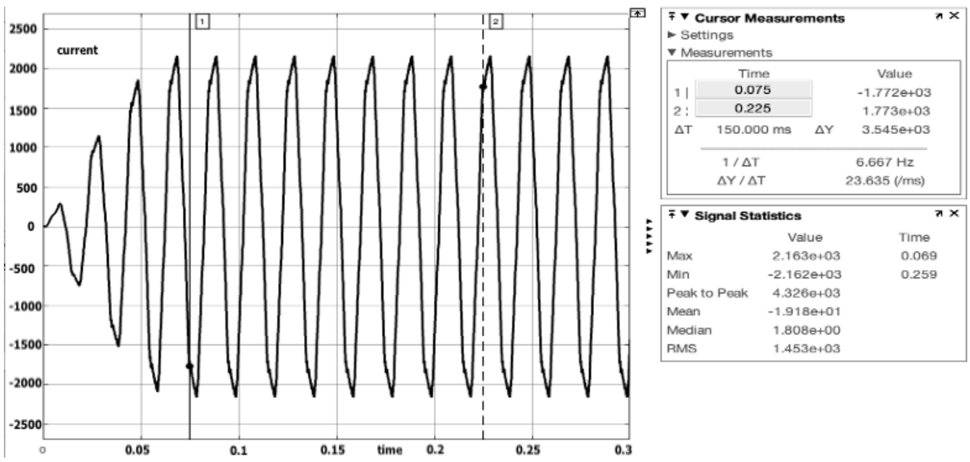

Figure 12. Post-STATCOM system current waveform

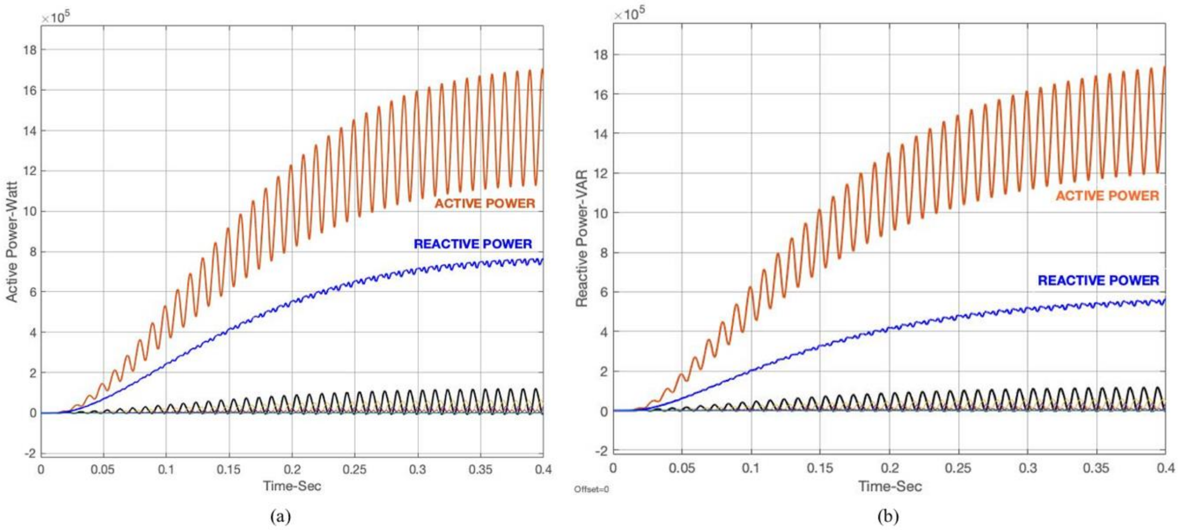

Figure 13. Active/ reactive power waveform (a) without and (b) with STATCOM

As a result of the Simulink simulation, the reactive power, active power and load current values of the system before and after the STATCOM application are given in Table-5.

Table 5. Simulation results values pre/post STATCOM

	Reactive Power-kVAR	**Current-kA**	**Active Power-MW**
Pre-STATCOM	782,45	1,645	1,125
Post-STATCOM	594,32	1,453	1,117

4. Result and Discussion

With the use of energy and the gradual decrease in energy reserves of traditional energy sources, renewable energy sources centred energy production has increased. Recent developments and the gaining of a more complex character of most users' load profiles reveal the necessity of improving the quality of the energy produced and transferred to the consumers. In this respect, the STATCOM application, also discussed in this study, significantly increases the power quality of the energy obtained from power systems. From the point reached with the survey, improvements and improvements have been achieved in the parameters that determine the power quality of the energy obtained from the power system. For example, if values such as current and voltage are transferred to loads and networks that cause possible harmonic and distortion, distortions in waveforms are reduced by STATCOM. RPC application provided a correction in the power coefficient and a decrease in the reactive power value. In addition to the improvement in the load current waveform, its value has also been reduced. In this way, an increase in the current-carrying capacity of the system was obtained, although the active power value did not change. The result is continuously regulating voltage and current on the transmission line, much more significant amounts of real power, preventing under-voltage or loss of power. This situation can be seen analytically, especially in Figures 10,12 and 13. 11,671% decrease in system current and a 24,043% decrease in system reactive power increased total system efficiency. The numerical data of this can be seen in Table 5.

Harmonic analyses of the output waveforms can be performed by expanding the study further, thus obtaining more mathematical expressions of the optimisation. Real-time operating parameter values of the plant can be added to the study. The manufactured sub-unit of the modelled STATCOM can be added to the power system, and the experimental content can be added to the survey.

Conflict of Interest

No conflict of interest was declared by the authors.

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