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Power quality improvement of a proposed grid-connected hybrid system by load flow analysis using static var compensator

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A R T I C L E I N F O

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A B S T R A C T

Renewable resources are most effective for sustainable development of society and economically efficient for small-scale power generation. However, grid integration is challenging because of the randomness of the source effects on power system parameters. This work proposes power quality enhancement by incorporating Static VAR Compensator (SVC) in a grid-integrated renewable hybrid power system. SVC is one of the shunt type Flexible AC Transmission Systems (FACTS) devices that is adopted in this system for the compensation of reactive power requirement. The proposed hybrid system for the Rohingya Refugee camp is energized by a wind and solar based sources. The objective is to enhance the overall bus voltage profile by minimizing both real and reactive power losses as well as boost the power transmission capability of the entire system. Different case studies have been considered by changing the source availability and generation supply for load flow analysis using ETAP software. Moreover, critical system parameters such as bus voltage, power transfer capacity, and power losses have been reported during the inactive time of one or both renewable sources. The results obtained without SVC have been compared against the ones with the presence of SVC. Our analysis reveals that, as a result of using SVC, the voltage profile improves by 2.9–3.3%, branch loss reduces by 2.1–2.4%, and power transfer capability enhances by 7.5–9 units.

1. Introduction

Renewable energy development is significant in this new era from different perspectives like modern technology, assessment of resources, system design, etc. and few countries have reached the double-digit share of renewable energy in power generation [1]. Bangladesh is a developing country with more than 160 million people where the power generation mostly depends on non-renewable energy rather than renewable energy [2]. The overall power generation efficiency varies between 34.9% and 36.3% in the period 2007 to 2016 and the renewable energy shares vary from 0.62% to 1.64% within this period [3]. Access to clean, reliable, and affordable energy is a basic human need at a household level. But it is difficult to fulfill the power demand as per expectation in a developing country. So, there is no alternative to renewable energy in places where electricity facility either unavailable or insufficient to meet the electricity demand. Hence, renewable energy generation has huge potential for sustainable development in this region [4–6]. To make the renewable energy (RE) system more reliable, one of the most important factors is power quality, and FACTS is amongst the most outstanding power electronics devices that contribute to power system stability in an efficient manner [7–9]. Earlier part of this research work depicted the feasibility analysis of the adopted site [10,11] by the same authors. This paper emphasizes on the power

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quality issue for the chosen power systems architecture.

1.1. Literature review

The power quality of a solar-wind based power system was studied in Ref. [12], where voltage mitigation, sag, swell and voltage stability were identified as the major challenging issues. The reason for these problems is the randomness and non-linear characteristics of renewable sources due to discontinuity of supply which depends entirely on nature. Due to these problems, it becomes challenging to rely solely upon renewable energy based generating schemes for obtaining electricity. Moreover, this also introduces challenges while the necessity of grid integration arises. To overcome these problems, extensive amount of research were conducted for introducing advanced technologies in the form of power electronics devices like FACTS. A modern optimization technique, namely Atom search optimization (ASO) was adopted to design a fractional-order proportional integral derivative (FOPID) controller for unified power quality conditioner (UPQC) in a renewable hybrid system [13]. The work succeeded to achieve a reduced overall power loss and total harmonic distortion (THD) for the system under consideration. The ASO-UPQC combination was also proposed for optimizing the power quality issues of a grid-integrated hybrid renewable energy system (HRES) [14]. Reactive power based sensitivity indices was proposed to identify the voltage instability issues in renewable energy based power system [14,15]. With the aid of the proposed indices, the enhancement in renewable energy penetration level into the grid was justified. Application of Static Synchronous Compensator (STATCOM) was proposed to improve the voltage profile of a wind-solar based renewable hybrid farm [16]. It was identified that the STATCOM could compensate for the necessary reactive power required by the HRES and increase the system reliability. Ref. [17] presented an analytical approach for examining the power quality related techno-economic issues of a renewable energy based power system incorporating FACTS devices. The analysis attempted to minimize the financial losses occurring due to various power quality indices such as voltage sag, voltage imbalance, cost associated with different harmonic mitigating solutions and relevant payback. The effectiveness of a number of FACTS devices such as SVC, STATCOM, and Static Synchronous Series Compensator (SSSC) was analyzed for maintaining voltage profiles in photovoltaic (PV) systems utilizing PV diagram [18]. The SVC technology was adopted for enhancing system voltage profile, reducing reactive power loss, and suppressing voltage fluctuation in the power system [19]. The SVC was integrated with two different IEEE benchmark power systems and the results showed significant improvement of the aforesaid parameters after installing SVC. Incorporation of Thyristor Controlled Series Compensator (TCSC), SVC, and STATCOM into renewable hybrid system improved the overall power quality [20]. A two area interconnected power system was tested for improving the power quality using voltage sources converter based FACTS devices like STATCOM, SSSC, and Unified Power Flow Controller (UPFC) [21]. The results indicated that with the incorporation of FACTS, the power loss got reduced and the system responses became faster compared to the system without FACTS. The allocation of FACTS device based on evolutionary algorithms in standard IEEE benchmark systems was studied in Ref. [22]. It was depicted that the introduction of FACTS enhanced the voltage stability margin of the entire system. A MATLAB/Simulink based grid-tied wind energy generation system was studied where improved bus voltage profile and increased system efficiency was obtained by the adoption of STATCOM [23]. The impacts of renewable energy sources' power flow control by incorporating SVC and TCSC was investigated in Ref. [24]. The work emphasized on the effectiveness of existing transmission lines for bulk power transfer which gave better performances by the inclusion of FACTS. A linear quadratic regulator (LQR) was utilized to eradicate the power quality related issues of a grid-integrated PV system feeding power to a non-linear load [25]. The analysis was conducted in MATLAB/Simulink environment which showed that the PV inverter compensated for the reactive power issues, reduced the THD, and yielded near-unity power factor. An extensive review on FACTS based power quality improvement for on-grid and off-grid renewable energy systems was conducted in Ref. [26]. The work demonstrated the adoption of a variety of conventional and adaptive algorithms to control the Distribution FACTS (DFACTS) with an aim to enhance the utility power quality with renewable energy penetration.

1.2. Contribution of paper

In this research, a FACTS device called SVC is used in the proposed grid-connected renewable hybrid system which stabilizes and enhances the bus voltage, compensates for the reactive power, and reduces the active power loss to ensure enhanced power transmission. The obtained outcome is compared to the results without using SVC. This proposed grid-connected renewable hybrid system is a power crisis solution for Teknaf nayapara Rohingya refugee camp. In this Camp 3733 family lives according to Refugee Relief and Reprobation Commission (RRRC) registration [11]. Considering 150 W load for each family this grid-connected hybrid system is proposed by incorporating the FACTS device. This Rohingya camp is located near the coastal area where renewable resources are available. To the best of the authors' knowledge, no previous work proposed the adoption of FACTS based renewable energy system for improving the power quality issues of the Rohingya refugee camp of Teknaf. Hence, the novelty of this study is to offer a reliable power supply solution for the refugees through the use of FACTS based renewable energy system.

1.3. Formation of paper

The remainder of the paper is organized as follows. Section 2 presents the details about the methodological formulation, basic structure, and characteristics of SVC. Section 3 discusses the proposed hybrid system configuration. Simulation results of the conducted case studies along with the critical discussions of the obtained results are described in Section 4. Section 5 concludes the present research and provides some future direction of the current work.

2. Mathematical modeling

In this proposed system the primary components are renewable generation sources (solar and wind), load, and FACTS devices. The details are discussed in the following subsections.

2.1. Solar PV system

The use of solar energy in power generation has been widely observed in recent years as it is a readily available renewable energy source in nature. Compared to other renewable energy sources, it became more popular around the world due to a range of technology introduced for converting solar energy into electricity. Using the photovoltaic effect, solar radiation is converted to electricity. According to the International Energy Agency under its 'Net Zero by 2050' report, about 20% of the world's total electricity generation will be contributed from solar energy. At present, China has the most solar plants installed [27].

A solar cell or photovoltaic cell is a combination of a p-type and n-type semiconductor called a p-n junction which is made of a thin layer of semiconductor material. An equivalent circuit of a solar cell is represented in Fig. 1 where a current source (I_{ph}), a diode, a series resistor (R_s), and a parallel resistor (R_{sh}) are included.

The characteristic of the solar panel used in this work is shown in Figs. 2 and 3. These figures describe the relationship between power vs. voltage (P–V) and current vs. voltage (I–V) of the solar panel, respectively [28].

The electrical characteristic data of the solar panel as obtained from Figs. 2 and 3 are given in Table 1.

2.2. Wind energy system

Wind energy is one of the best renewable energy sources around the world. Wind energy is converted into electrical energy through the mechanical system. For the conversion of wind energy into electricity, various types of wind turbines are used like synchronous generators, permanent magnet synchronous generators (PMSG), induction generators, and doubly-fed induction generators. The extractable power from the wind is expressed as in Eq. (1) [29]:

$$P_{avail} = \frac{1}{2} * \rho * A * V^3 * C_p \tag{1}$$

where ρ is the density of air, A is swept area of turbine blades, V is the wind speed, and C_p is the power coefficient. The blade swept are can be expresses as in Eq. (2):

$$A = \pi r^2 \tag{2}$$

where the radius(r) is the turbine blade length.

No wind turbine can convert more than 59.3% of the kinetic energy of the wind into mechanical energy by turning a rotor as per German physicist Albert Betz in 1919. Hence, this value (59.3%) serves as the upper limit of wind energy conversion and termed as the Betz limit. However, in practice, the Betz limit is difficult to attain even with the best-designed wind turbine, and the practical value of power coefficient lies within 35%–45%. In addition to this, there are many other factors of an entire wind power generation scheme like generators, converter, gearbox, shaft, and so on. By considering all of this, only 10–30% of wind power is converted into useable

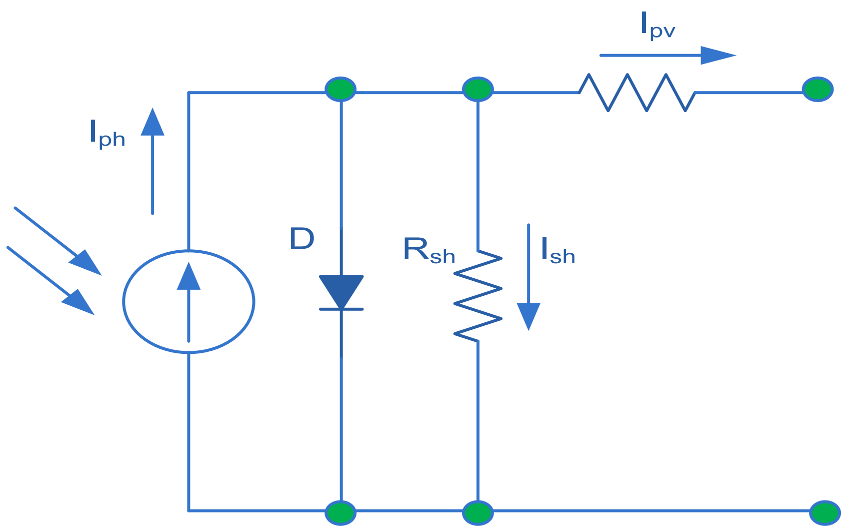


Fig. 1. The equivalent circuit of the solar cell.

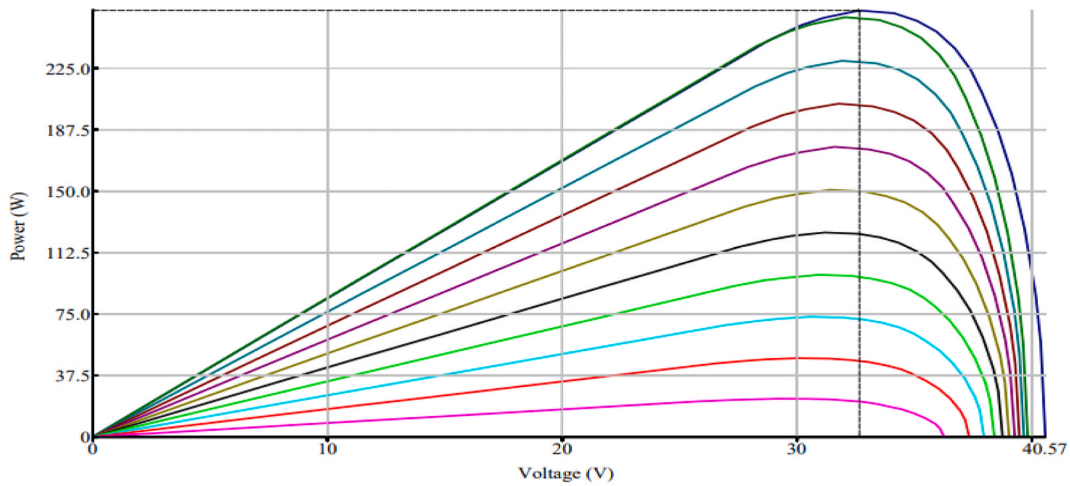


Fig. 2. P–V curve of the solar panel.

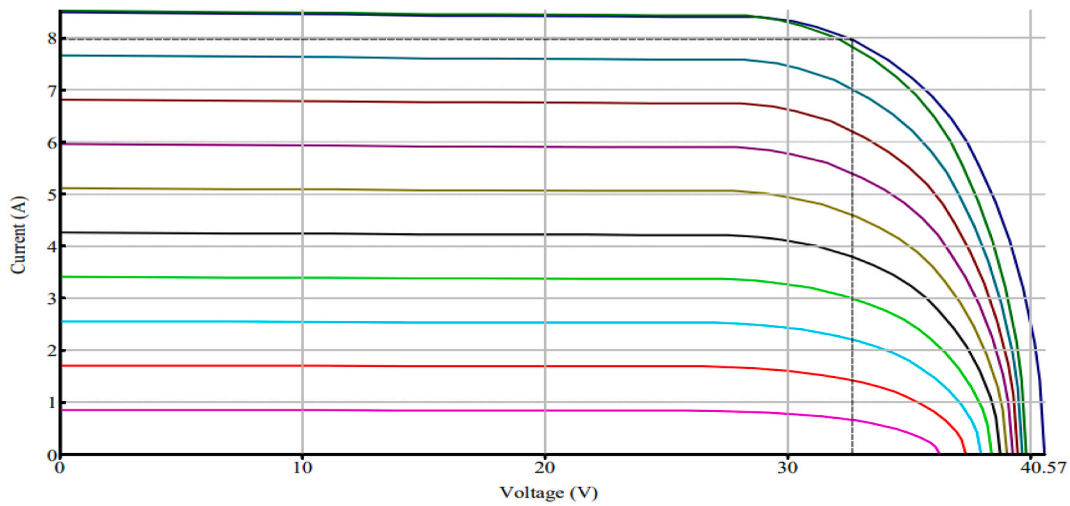


Fig. 3. I–V curve of the solar panel.

Table 1
Electrical parameters of solar panel.

Electrical characteristics at a standard temperature condition	
Maximum Power (P_{max})	260.2 W
Power Tolerance	0 ~ +7.7 W
Panel efficiency	14.2%
Current at maximum power point (I_{mp})	7.97 A
Voltage at maximum power point (V_{mp})	32.65 V
Short Circuit Current (I_{sc})	8.49 A
Open Circuit Voltage (V_{oc})	40.57 V
Solar Radiation [10,11]	4.76 kWh/m^2/day

electricity.

2.3. Load

Constant PQ (real and reactive) load has been considered in this work. The power factor is a very important issue; according to the Bangladesh power system (BPS) the power factor varies from 0.85 to 0.95 [30]. The power factor at the load buses has been chosen as 0.95, lagging in this work.

2.4. Static VAR Compensator (SVC)

Shortage of reactive power causes voltage sag which ultimately leads the system to voltage instability. Shortage of reactive power provides a reduced level of voltage, and on the other hand, surplus reactive power causes the power loss of the transmission line. To provide controlled reactive power in the system, the shunt FACTS device like SVC can be used. It provides reactive power in a controlled manner which in turn increases the system capacity of power transmission as well as the stability [31].

SVC is a controlled shunt susceptance device that can inject or absorb reactive power depending on the necessity. The control objective of the SVC is to maintain a desired voltage level in the system. As observed in Fig. 4, since the value of reactive power ($+Q_{CAP}$) provided by the fixed capacitor (FC) is constant, the resultant reactive power (Q_{NET}) injected into the system is controlled by the level of reactive power (Q_{IND}) absorbed by the thyristor controlled reactor (TCR). The firing angle of the anti-parallel thyristor can produce variable reactance [32].

The SVC can operate in two separate modes: one is voltage control mode and the other is VAR control mode. When it operates in voltage regulation mode, it follows the following characteristic curve shown in Fig. 5.

The fundamental component of the TCR current, I_{SVC} is obtained by Fourier analysis. The analytical expression of I_{SVC} can be given as in Eq. (3):

$$I_{SVC} = B_{TCR}(\sigma)U; \tag{3}$$

where, $\sigma = 2\,(\Pi - \alpha)$, $X_L = \omega L$, $B_{TCR}(\sigma)$ denotes an adjustable fundamental-frequency susceptance, σ is the angle for which a thyristor conducts, and α is the firing or delay angle. The dependence of $B_{TCR}(\sigma)$ on σ is shown in Eq. (4):

$$B_{TCR} = (\sigma - \sin\sigma) / \pi X_L \tag{4}$$

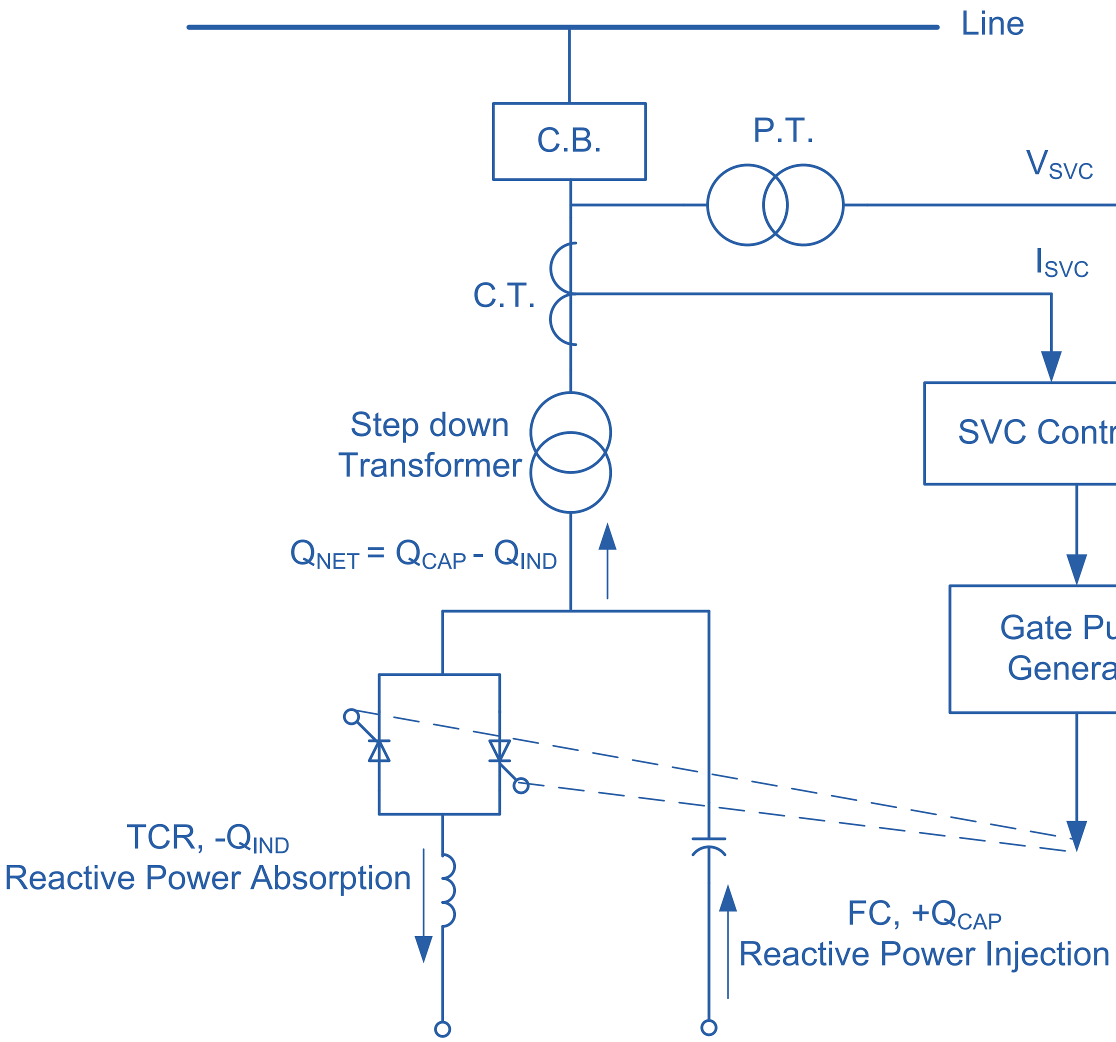


Fig. 4. Basic construction of SVC [30].

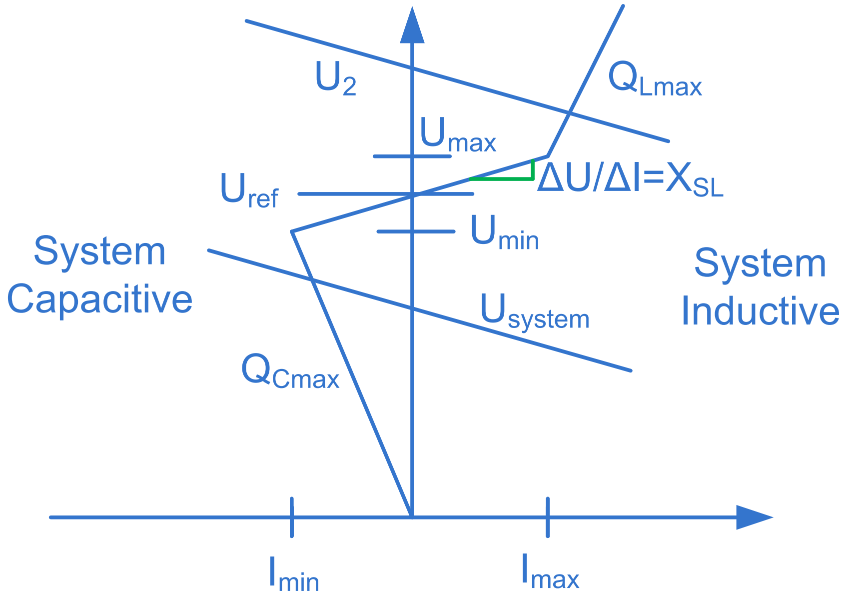


Fig. 5. Characteristic curve of SVC [30].

3. Proposed hybrid system configuration

This proposed system is mainly focused to improve the voltage profile, enhance the active power transfer capability, and reduce the branch losses in the network. The variability of renewable sources introduces an unwanted fluctuation in system voltage. Moreover, as most of consumers' demand is inductive in nature, the reactive power absorbed from the distribution system causes a dip in the voltage

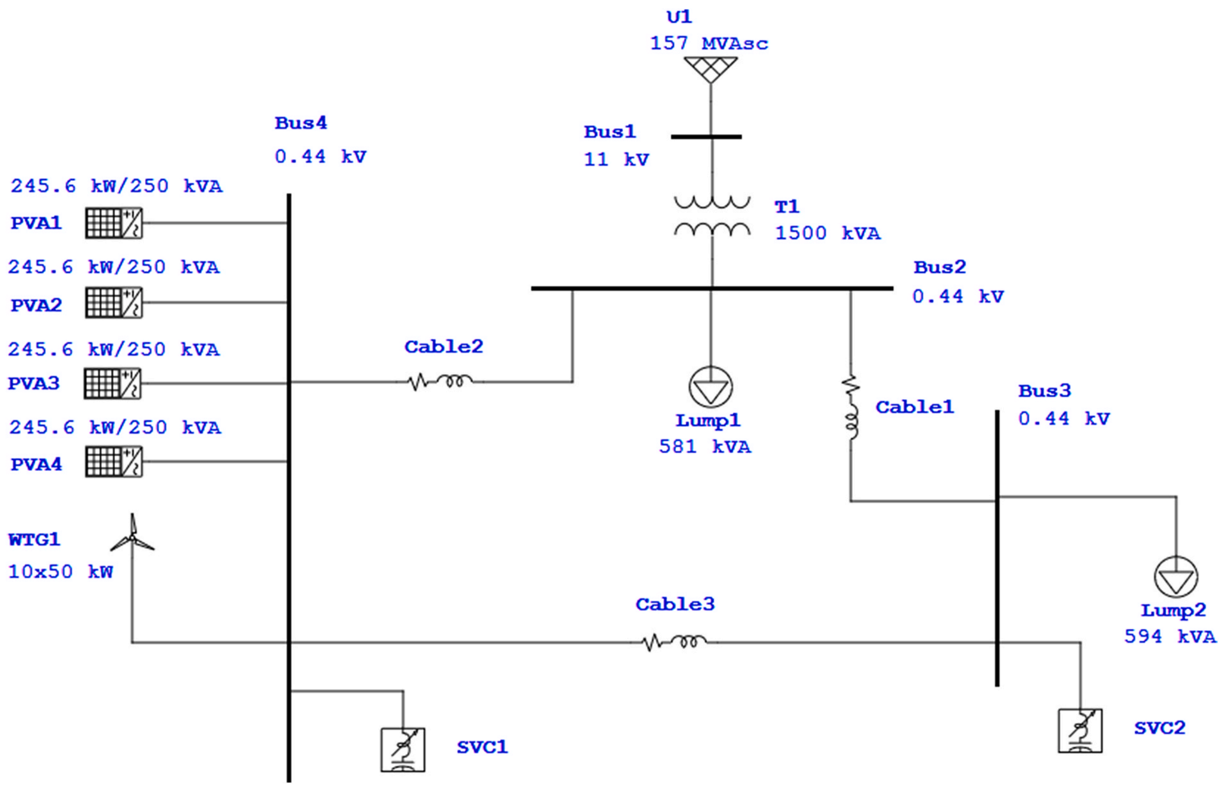


Fig. 6. Single line diagram of proposed grid-connected PV-Wind renewable hybrid system using SVC.

profile. Due to reactive power reduction in the system, transmission loss increases and the system becomes inefficient. FACTS device is a great innovation for improving the power quality. Therefore, in this work, the inclusion of a FACTS device named Static VAR Compensator (SVC) in the network system is proposed. The single line diagram (SLD) of the proposed system is shown in Fig. 6.

In this grid-connected hybrid system, an 11/.440 kV distribution system is proposed with 4 buses as of Fig. 6. This system is proposed for Teknaf Nayapara Rohingya refugee camp where 3732 families registered as per the Refugee Relief and Reprobation Commission (RRRC) report. Approximately 1.5 MW grid-connected solar wind hybrid system is designed considering an 80-W fan, two energy bulbs of 30 W, and other 10-W loads for each household. The system consists of four PV arrays, each rated 245.6 kW. The output of each PV array is fed through a 250 kVA inverter for necessary conversion from DC to AC. Moreover, ten wind turbines, each rated 50 kW, are installed at the voltage control bus 4, while the utility is used as the slack or swing bus 1. Two lump loads of 581 kVA and 594 kVA rating are connected at load bus 2 and 3, respectively. The wind turbine and solar panel sizes are selected from an earlier case study where the authors simulated a cost-effective 1.5 MW grid-connected hybrid system for the same location using HOMER software [11]. Furthermore, a distribution transformer used has a rating of 1.5 MVA. The two SVCs (rating of 2 VAR inductive and 3 VAR capacitive) are placed at bus 3 & 4 where voltage fluctuation is more. The SVC rating is selected through extensive simulation where the given rating provided the best result. The location of the SVCs are decided based on the seven scenarios conducted for this study. Design data are provided in Table 2.

According to the availability of the sources, the following configurations are simulated for finding the power quality (Parameters) of the proposed system. Tables 3 and 4 represent case studies 1 and 2 comprising of 7 different scenarios based on the availability and output percentage variation of adopted resources.

The main purpose of study 1 is to observe the system response when two renewable sources are completely out of service or one source is out of service and the other is in service.

Study 2 is to observe the system when two renewable sources are in service, but the output is changing due to the variation of nature.

4. Simulation result & discussion

In this research, the combination of the solar PV panel and wind turbine is used for designing a grid-connected hybrid renewable energy system. The complete proposed system analysis representations are given below.

4.1. Simulation tools

In this work, ETAP (Electrical Transient Analyzer Program) simulation software has been used. This simulation module has many features such as power system analysis, real-time simulation monitoring, and optimized control. It is the most comprehensive analysis software made especially to design and apply tests of power systems. This software was developed by Operation Technology Inc. [28, 33]. ETAP software is used in this research for power flow analysis and monitoring the different power quality of the designed system.

4.2. Load flow analysis

The main purpose of analyzing load flow in ETAP is to get detailed information about the characteristics of the power system under various supply and load conditions with the presence and absence of SVCs. From this load flow simulation, the information of voltage regulation, power loss in the transmission network, and current flow of the system have been obtained. Seven cases were considered under the two study observations, which are shown in Figs. 7–20 and Tables 5–11.

4.2.1. Scenario -1

When wind turbine and PV array are active, the parameters of average bus voltage, average active power flow, and average voltage drop are 99.2%, 256.7 kW, and 1.39% respectively. After the addition of SVCs, the average bus voltage improves to 99.6%, the average active power increases from 256.7 kW to 257.0 kW, and the average branch voltage drop is reduced by 0.31%.

Table 2
System parameters connected at each bus.

Source	Quantity	Rating	Bus Number
Transformer	1	1500 kVA	1 & 2
PV Array1	1	245.6 KW	4
PV Array2	1	245.6 KW	4
PV Array3	1	245.6 KW	4
PV Array4	1	245.6 KW	4
Wind Turbine	10	50.0 KW	4
SVC	2	2 VAR inductive and 3 VAR Capacitive	4
Lumped Load1	1	581 kVA	2
Lumped Load2	1	594 kVA	3

Table 3
Case study-1 depending on connectivity.

Study:1	WTG	PV array	Power Grid	Details
Scenario-1	In service	In service	In service	All the sources are working
Scenario-2	out of service	In service	In service	Wind turbines are out of service, PV array, and grid supply the required power
Scenario-3	In service	out of service	In service	Only grid and wind turbine supply the demand
Scenario-4	out of service	out of service	In service	Only grid fulfill the load requirement

Table 4
Case study-2 depending on percentage (%) of renewable energy contribution.

Study:2	WTG	PV array	Power Grid	Details
Scenario-5	WTG output 40%	PV array output 90%	In service	Considering peak supply from the renewable sources
Scenario-6	WTG output 20%	PV array output 35%	In service	When wind speed is reasonable and the weather is gloomy
Scenario-7	WTG output 5%	PV array output 20%	In service	Minimum output considered from renewable sources

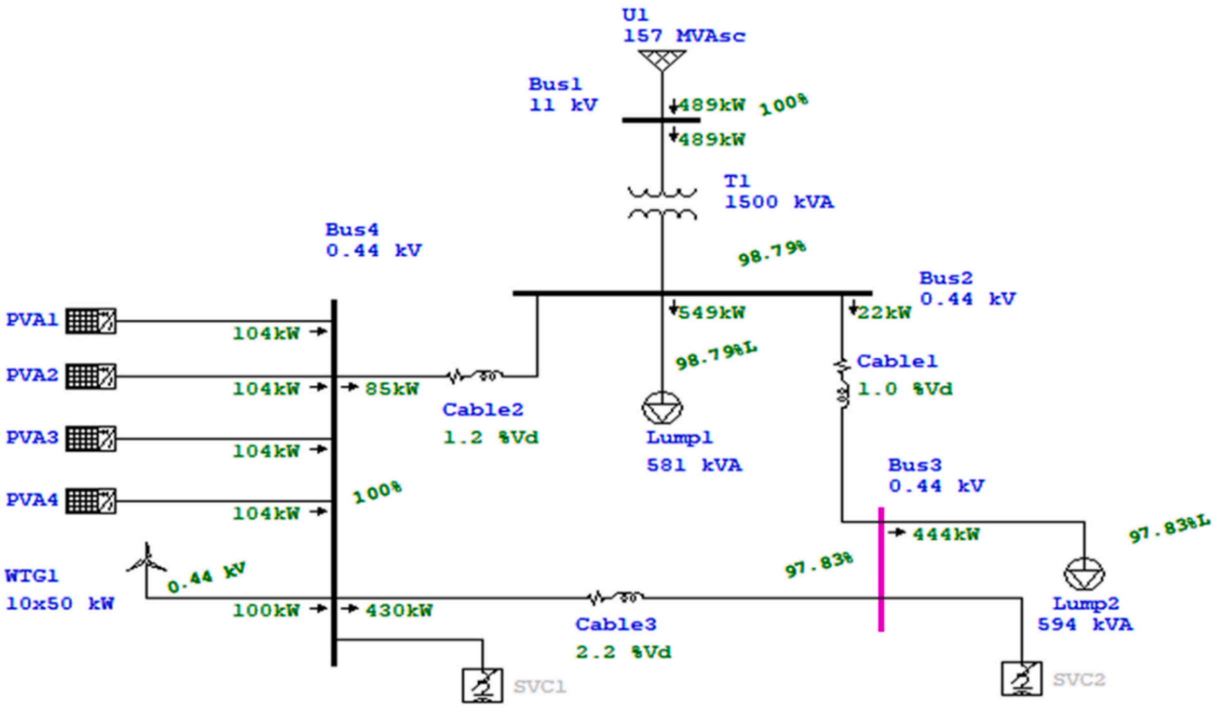


Fig. 7. Load flow analysis of scenario-1 when SVCs are inactive.

4.2.2. Scenario -2

When the PV array is active and the wind turbine is inactive, the parameters of average bus voltage, average active power flow, and average voltage drop are 99.2%, 267.7 kW, and 1.31% respectively. After the addition of SVC, the average bus voltage improves to 99.4%, the average active power remains the same, and the average branch voltage drop is reduced by 0.39%.

4.2.3. Scenario -3

When the wind turbine is active and the PV array is inactive, the parameters of average bus voltage, average active power flow, and average voltage drop are 96.4%, 374.3 kW, and 2.89% respectively. After the addition of SVC, the average bus voltage improves to 99.3%, the average active power increases from 374.3 kW to 381.8 kW, and the average branch voltage drop is reduced by 2.11%.

4.2.4. Scenario -4

When wind turbine and PV array are inactive, the parameters of average bus voltage, average active power flow, and average voltage drop are 95.9%, 415.8 kW, and 3.31% respectively. After the addition of SVC, the average bus voltage improves to 99.2%, the average active power increases from 415.8 kW to 424.8 kW, and the average branch voltage drop is reduced by 2.43%.

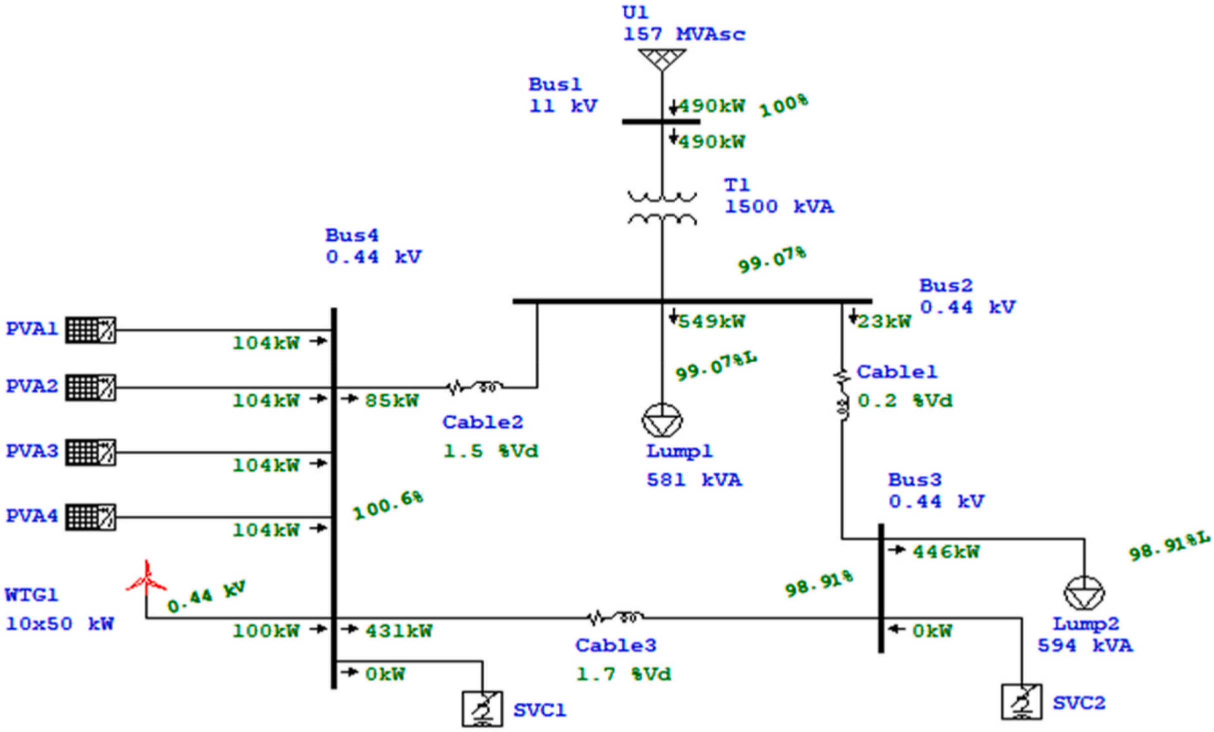


Fig. 8. Load flow analysis of scenario-1 when SVCs are active.

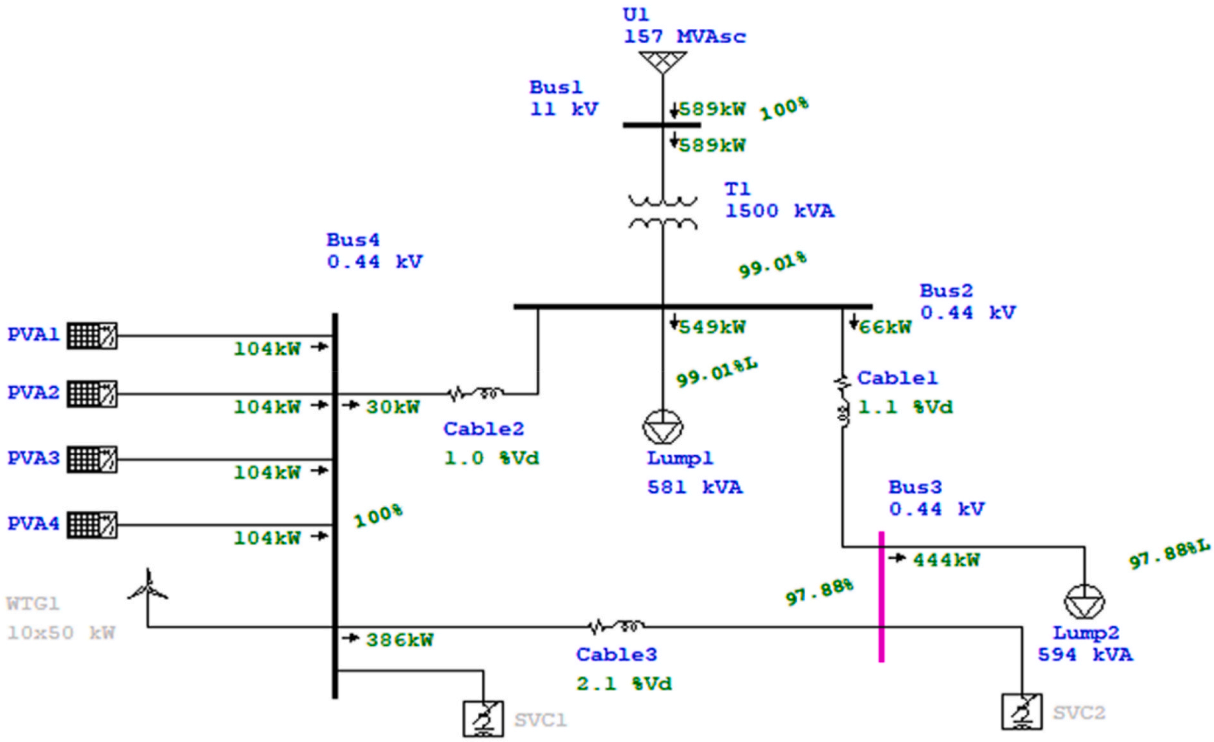


Fig. 9. Load flow analysis of scenario-2 when SVCs are inactive.

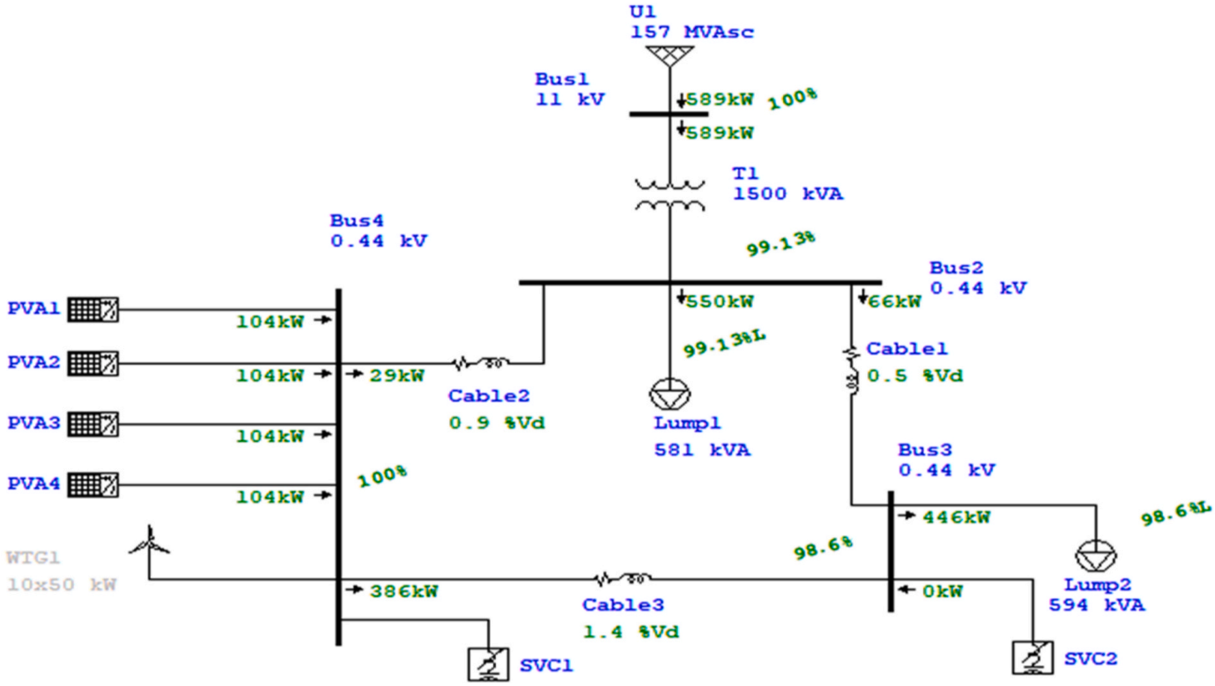


Fig. 10. Load flow analysis of scenario-2 when SVCs are active.

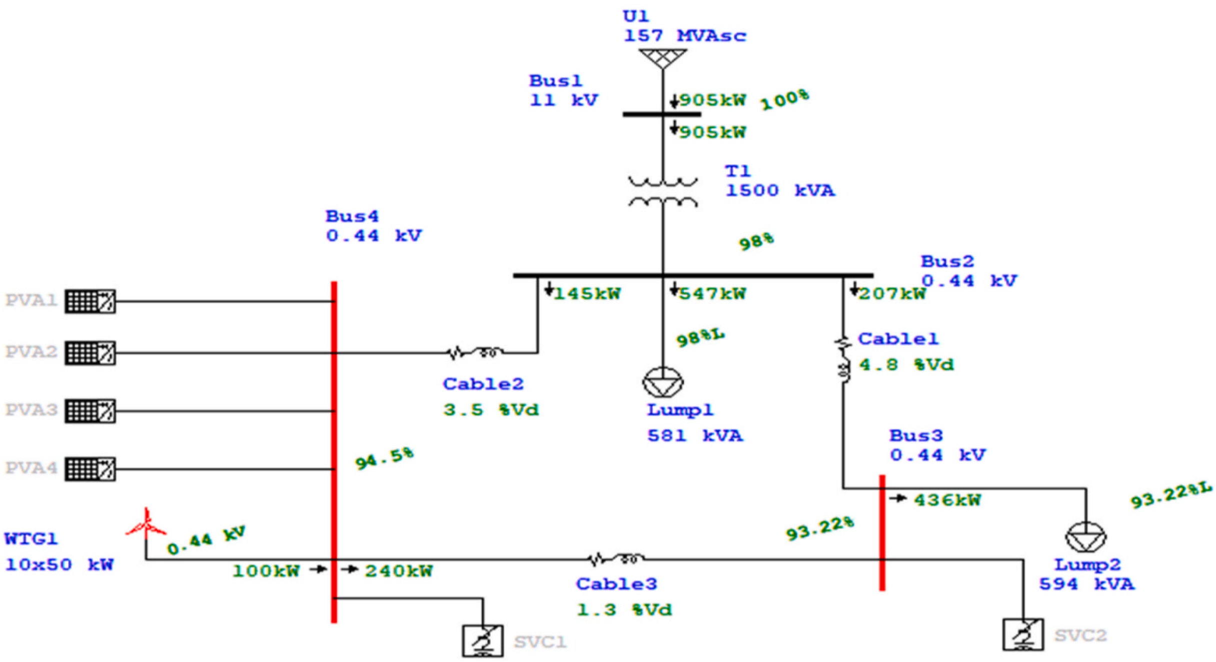


Fig. 11. Load flow analysis of scenario-3 when SVCs are inactive.

4.2.5. Scenario -5

When the wind and PV array is active but the output of the wind turbine is 40% and PV array output is 90%, at that time the parameters of average bus voltage, average active power flow, and average branch voltage drop are 100.1%, 302.3 kW and 2.28% respectively. After the addition of SVC, the average bus voltage decreases a little bit, the average branch voltage drop is reduced by 0.16%, and the average active power increases slightly.

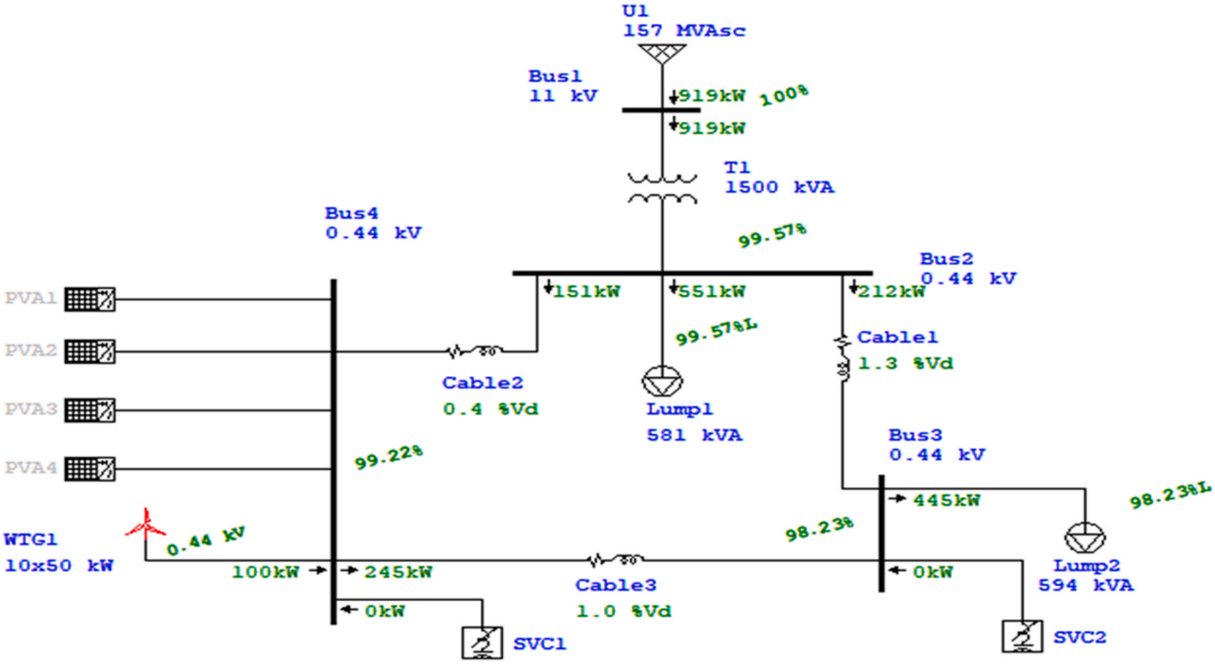


Fig. 12. Load flow analysis of scenario-3 when SVCs are active.

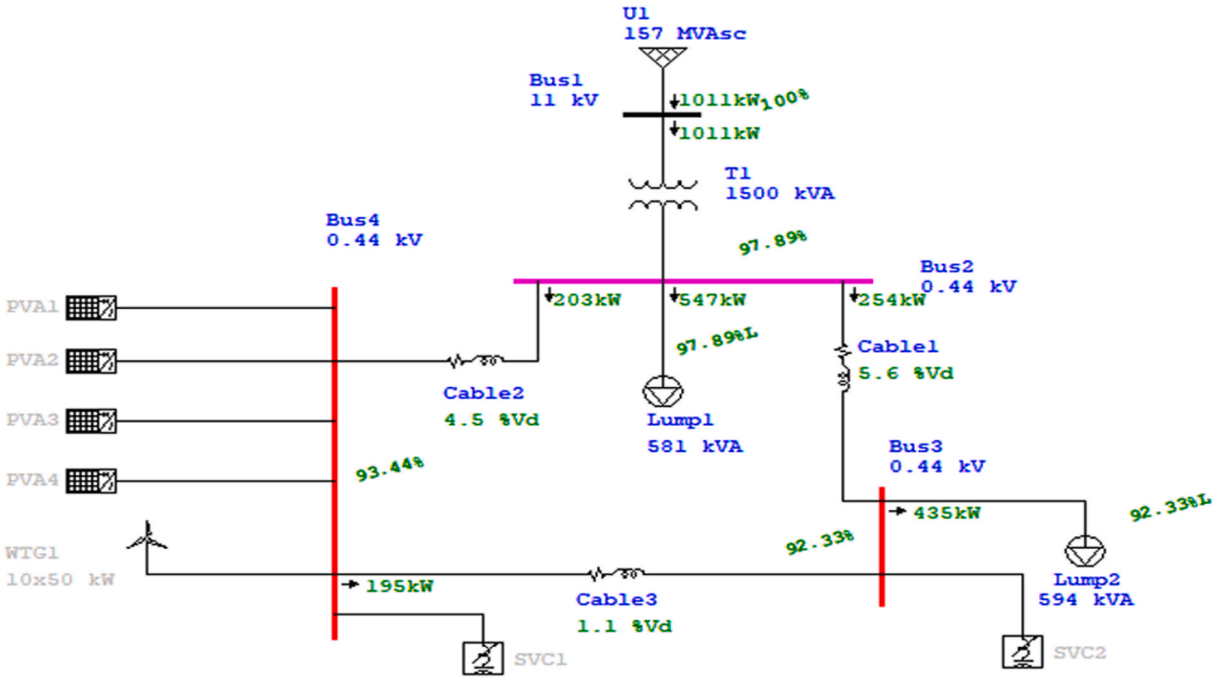


Fig. 13. Load flow analysis of scenario-4 when SVCs are inactive.

4.2.6. Scenario -6

When wind and PV array is active but the output of the wind turbine decreases to 20% and the PV array output decreases to 35%, of the average bus voltage, average active power flow, and average branch voltage drop are 99.2%, 266.0 kW and 1.32% respectively. After the addition of SVC, the average bus voltage and the average active power increases slightly, and the average branch voltage drop is reduced by 0.38%.

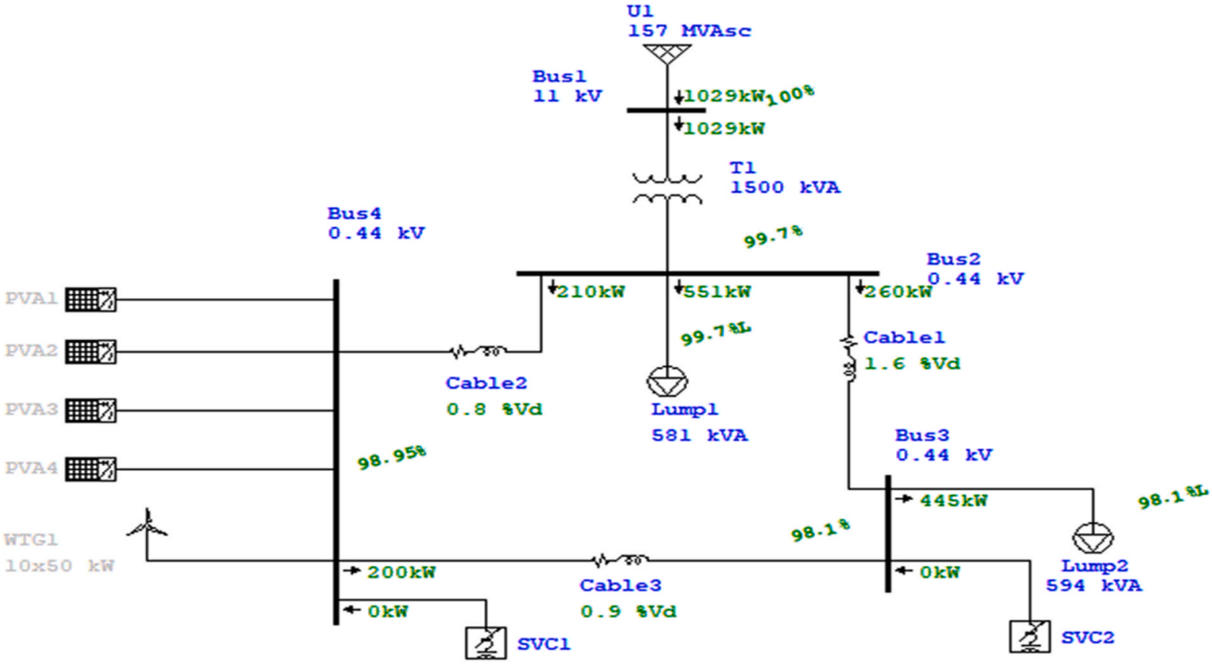


Fig. 14. Load flow analysis of scenario-4 when SVCs are active.

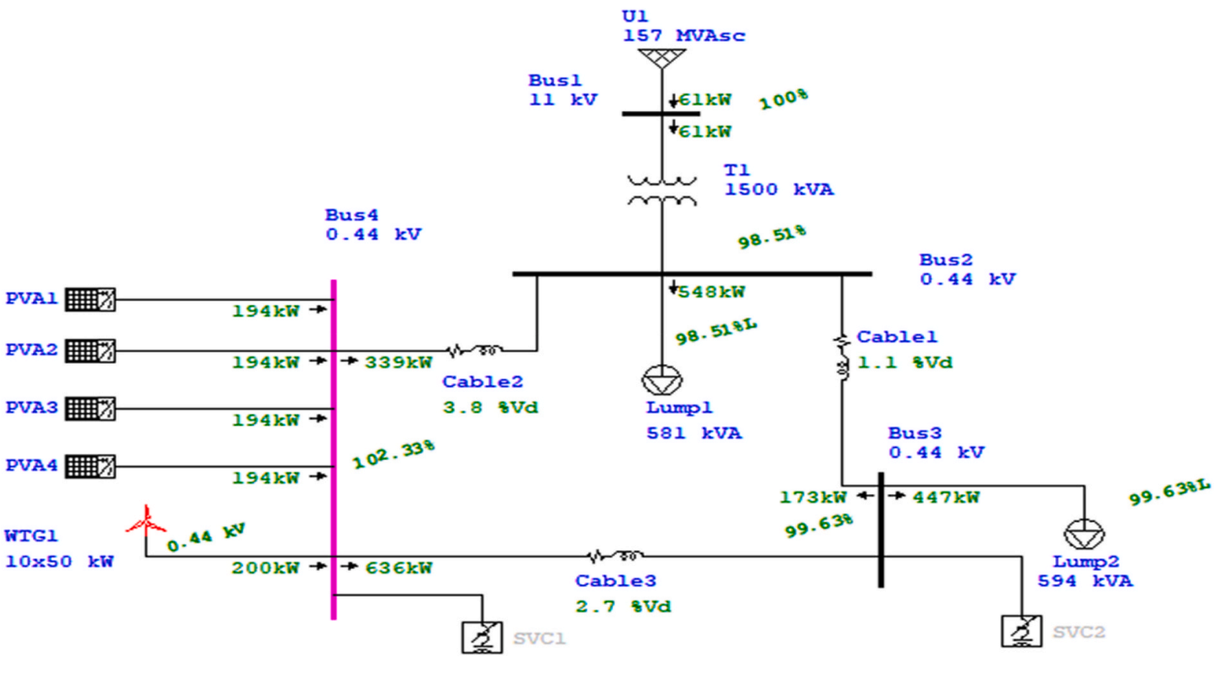


Fig. 15. Load flow analysis of scenario-5 when SVCs are inactive.

4.2.7. Scenario -7

When wind and PV arrays are active but wind turbine and PV arrays output is further reduced to 5% and 20% respectively, then the values of average bus voltage, average active power flow, and average voltage drop are 98.2%, 320.5 kW, and 1.61% respectively. After the addition of SVC, the average bus voltage improves to 99.5%, the average active power increases from 320.5 kW to 324.0 kW, and the average branch voltage drop is reduced by 0.80%.

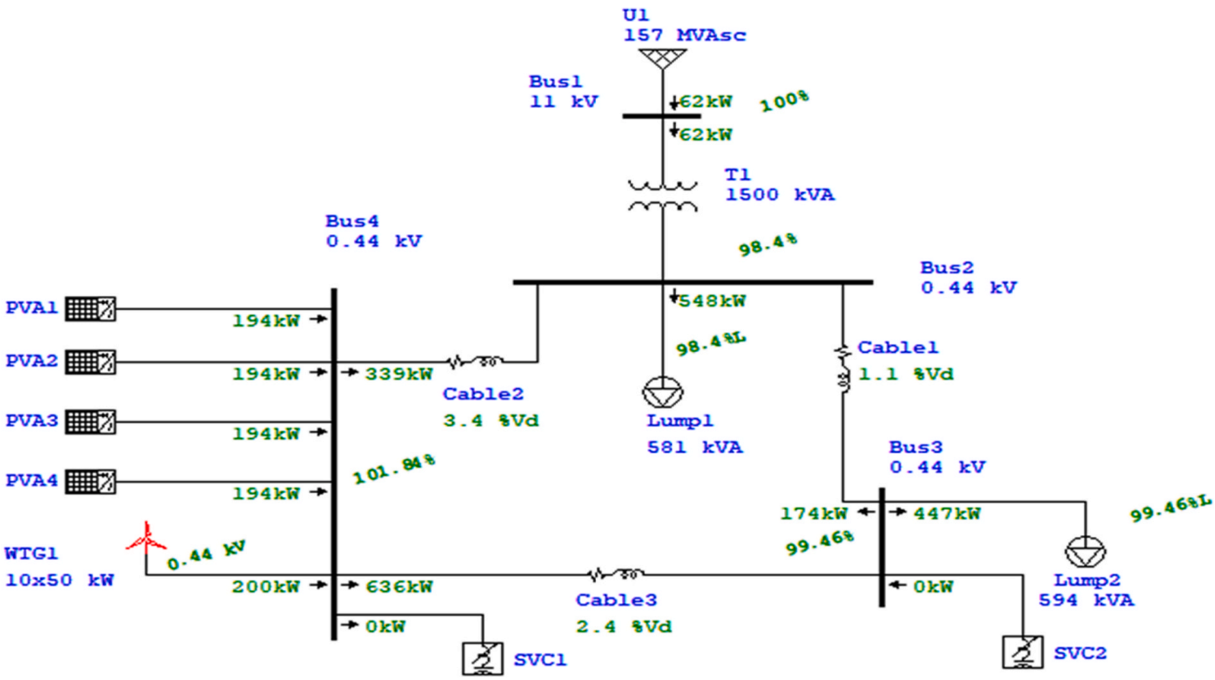


Fig. 16. Load flow analysis of scenario-5 when SVCs are active.

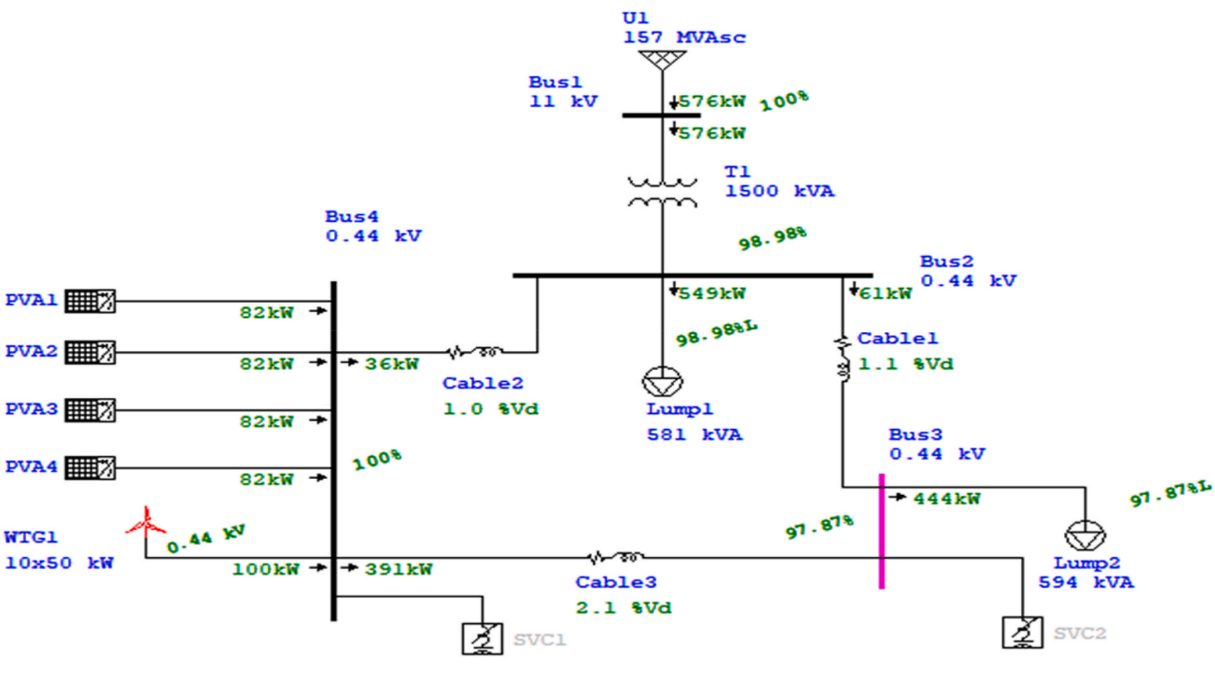


Fig. 17. Load flow analysis of scenario-6 when SVCs are inactive.

4.3. Performance analysis of all seven scenarios

FACTS device has outstanding performance in power system control, transient and steady-state stabilization that increases the efficiency of operation and functionality of existing power transmission and distribution systems. To maintain bus voltage magnitude in shunt compensation Static VAR Compensator (SVC) is used in this proposed system, which is one kind of FACTS device.

A summary of all seven scenarios without SVC is given in Table 12. Active generation sources are denoted by $\surd$ while the inactive

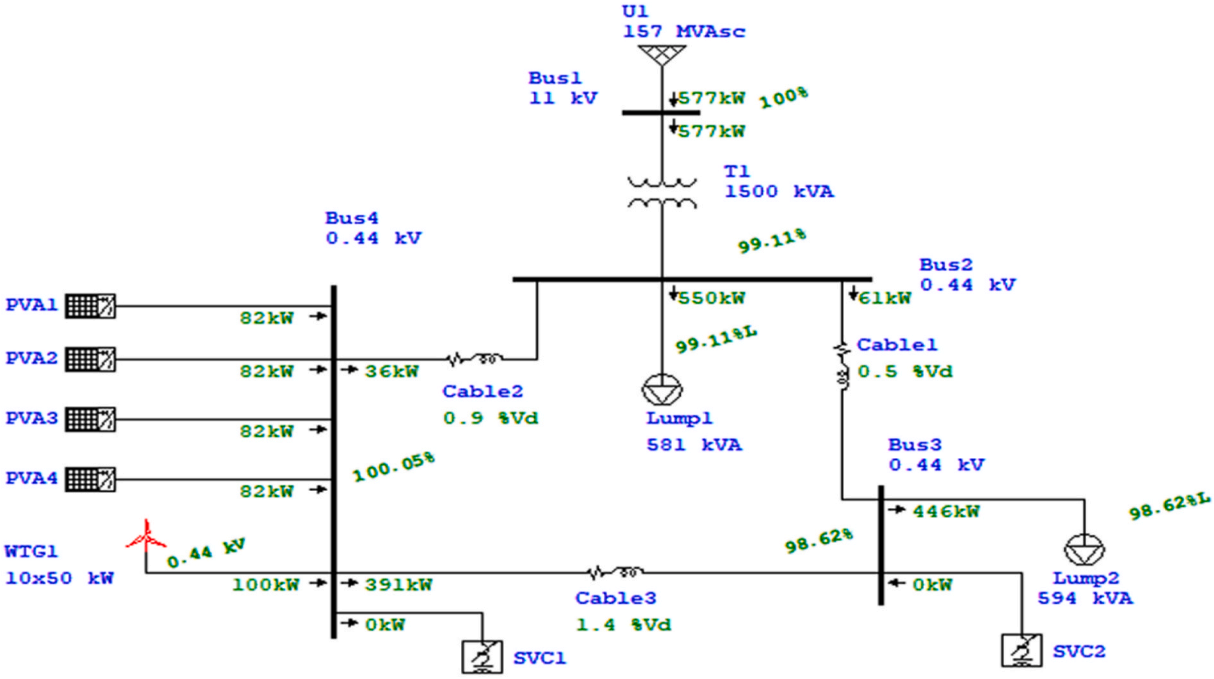


Fig. 18. Load flow analysis of scenario-6 when SVCs are active.

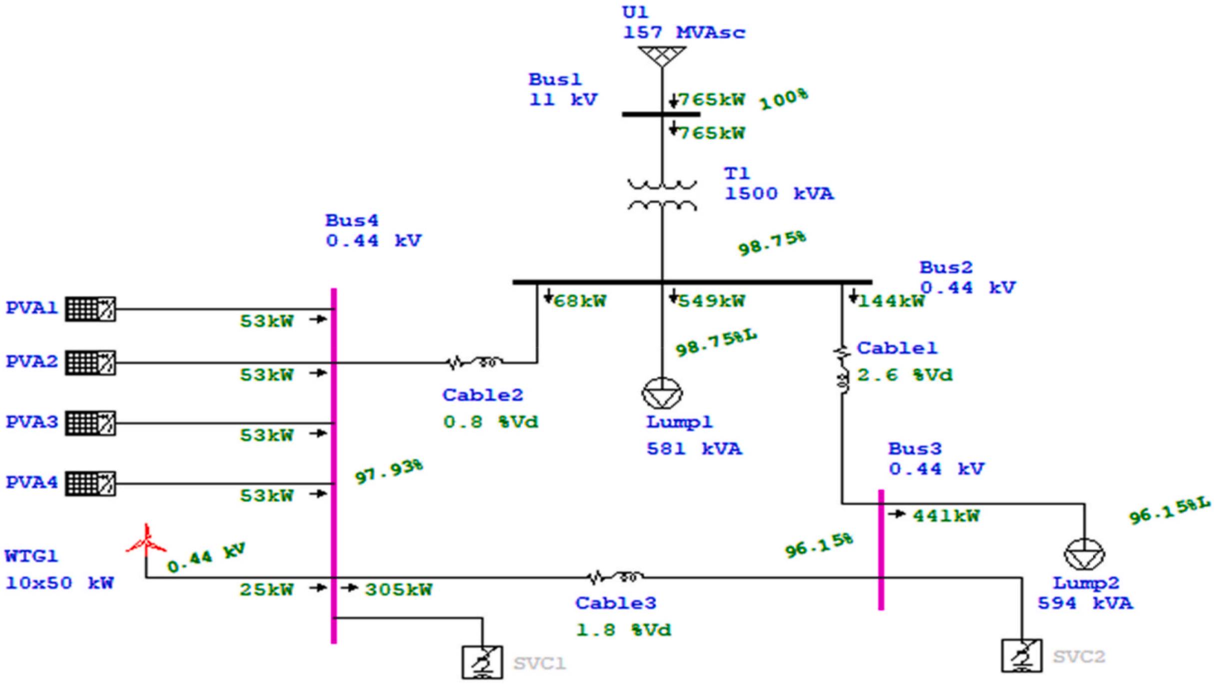


Fig. 19. Load flow analysis of scenario-7 when SVCs are inactive.

sources are denoted by X.

The system responses after the introduction of SVC are depicted in Figs. 21–25. The obtained value of bus voltage, without SVC and with SVC is shown in Figs. 21 and 22. It is observed that the average voltage increases from 98.3% to 99.5% with SVCs. Moreover, the average active power transfer capability increases from 314.7 kW to 317.7 kW, and branch losses decrease by 0.94% after using SVC. Details are given in Figs. 23–25.

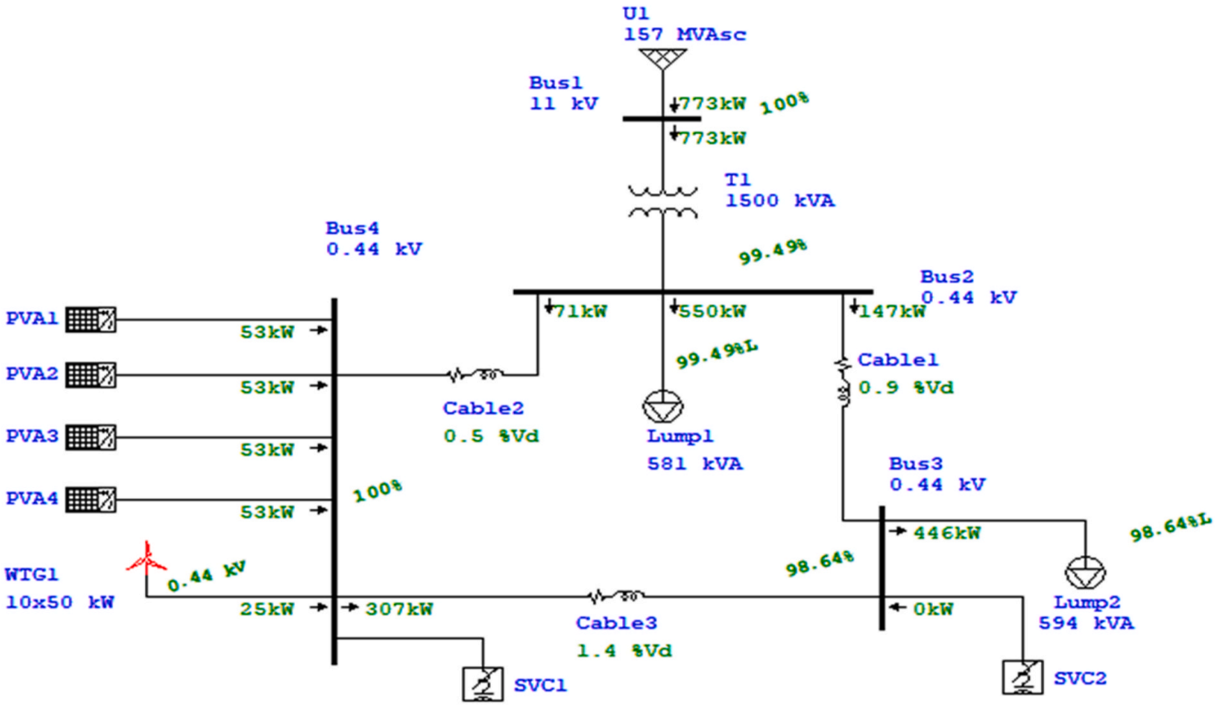


Fig. 20. Load flow analysis of scenario-7 when SVCs are active.

Table 5
Scenario-1: Comparative result of load flow analysis with and without SVCs.

Bus No	Voltage Profile (%)		From Bus	To Bus	Active Power (kW)		Voltage Drop (%)	
	Without SVC	With SVC			Without SVC	With SVC	Without SVC	With SVC
Bus1	100.0	100.0	Bus1	Bus2	489.0	490.0	1.21	0.93
Bus2	98.8	99.1	Bus2	Bus3	22.4	22.6	0.96	0.16
Bus3	97.8	98.9	Bus4	Bus2	85.4	84.6	1.21	1.53
Bus4	100.0	100.6	Bus4	Bus3	430.0	431.0	2.17	1.69
AVG	99.2	99.6			256.7	257.0	1.39	1.08

Table 6
Scenario-2: Comparative result of load flow analysis with and without SVCs.

Bus No	Voltage Profile (%)		From Bus	To Bus	Active Power (kW)		Voltage Drop (%)	
	Without SVC	With SVC			Without SVC	With SVC	Without SVC	With SVC
Bus1	100.0	100.0	Bus1	Bus2	589.0	589.0	0.99	0.87
Bus2	99.0	99.1	Bus2	Bus3	66.1	66.4	1.13	0.53
Bus3	97.9	98.6	Bus4	Bus2	29.6	29.5	0.99	0.87
Bus4	100.0	100.0	Bus4	Bus3	386.0	386.0	2.12	1.40
AVG	99.2	99.4			267.7	267.7	1.31	0.92

Table 7
Scenario -3: Comparative result of load flow analysis with and without SVCs.

Bus No	Voltage Profile (%)		From Bus	To Bus	Active Power (kW)		Voltage Drop (%)	
	Without SVC	With SVC			Without SVC	With SVC	Without SVC	With SVC
Bus1	100.0	100.0	Bus1	Bus2	905.0	919.0	2.00	0.43
Bus2	98.0	99.6	Bus2	Bus3	207.0	212.0	4.78	1.34
Bus3	93.2	98.2	Bus4	Bus2	145.0	151.0	3.50	0.35
Bus4	94.5	99.2	Bus4	Bus3	240.0	245.0	1.28	0.99
AVG	96.4	99.3			374.3	381.8	2.89	0.78

Table 8
Scenario -4: Comparative result of load flow analysis with and without SVCs.

Bus No	Voltage Profile (%)		From Bus	To Bus	Active Power (kW)		Voltage Drop (%)	
	Without SVC	With SVC			Without SVC	With SVC	Without SVC	With SVC
Bus1	100.0	100.0	Bus1	Bus2	1011.0	1029.0	2.11	0.30
Bus2	97.9	99.7	Bus2	Bus3	254.0	260.0	5.56	1.61
Bus3	92.3	98.1	Bus4	Bus2	203.0	210.0	4.46	0.75
Bus4	93.4	99.0	Bus4	Bus3	195.0	200.0	1.11	0.86
AVG	95.9	99.2			415.8	424.8	3.31	0.88

Table 9
Scenario -5: Comparative result of load flow analysis with and without SVCs.

Bus No	Voltage Profile (%)		From Bus	To Bus	Active Power (kW)		Voltage Drop (%)	
	Without SVC	With SVC			Without SVC	With SVC	Without SVC	With SVC
Bus1	100.0	100.0	Bus1	Bus2	61.1	61.6	1.49	1.60
Bus2	98.5	98.4	Bus2	Bus3	173.0	174.0	1.12	1.06
Bus3	99.6	99.5	Bus4	Bus2	339.0	339.0	3.82	3.44
Bus4	102.3	101.8	Bus4	Bus3	636.0	636.0	2.70	2.38
AVG	100.1	99.9			302.3	302.7	2.28	2.12

Table 10
Scenario -6: Comparative result of load flow analysis with and without SVCs.

Bus No	Voltage Profile (%)		From Bus	To Bus	Active Power (kW)		Voltage Drop (%)	
	Without SVC	With SVC			Without SVC	With SVC	Without SVC	With SVC
Bus1	100.0	100.0	Bus1	Bus2	576.0	577.0	1.02	0.89
Bus2	99.0	99.1	Bus2	Bus3	60.7	61.0	1.11	0.49
Bus3	97.9	98.6	Bus4	Bus2	36.5	36.2	1.02	0.94
Bus4	100.0	100.1	Bus4	Bus3	391.0	391.0	2.13	1.43
AVG	99.2	99.4			266.0	266.3	1.32	0.94

Table 11
Scenario -7: Comparative result of load flow analysis with and without SVC.

Bus No	Voltage Profile (%)		From Bus	To Bus	Active Power (kW)		Voltage Drop (%)	
	Without SVC	With SVC			Without SVC	With SVC	Without SVC	With SVC
Bus1	100.0	100.0	Bus1	Bus2	765.0	773.0	1.25	0.51
Bus2	98.8	99.5	Bus2	Bus3	144.0	147.0	2.60	0.85
Bus3	96.2	98.6	Bus4	Bus2	67.9	68.9	0.82	0.51
Bus4	97.9	100.0	Bus4	Bus3	305.0	307.0	1.78	1.36
AVG	98.2	99.5			320.5	324.0	1.61	0.81

5. Conclusions

This research explored the effectiveness of a Static VAR Compensator (SVC) in a grid integrated solar-wind hybrid system. Load flow analysis was carried out using ETAP for observing the improvement of power quality after the installation of SVCs in the proposed

Table 12
Summary of all seven scenarios without SVC.

	Wind Turbine	PV Array	Grid	Analysis
Study-1				System response with at least one renewable source unavailable
Scenario-1	✓	✓	✓	Under voltage at bus 2 and bus 3.
Scenario-2	X	✓	✓	Similar response to case 1.
Scenario-3	✓	X	✓	Under voltage at Buses 3 and 4, increased branch loss.
Scenario-4	X	X	✓	The entire network is in low voltage.
Study-2				System response with variable renewable source outputs
Scenario-5	Output 40%	Output 90%	✓	Overvoltage at the bus nearest to the wind turbine.
Scenario-6	Output 20%	Output 35%	✓	Same as scenarios-2
Scenario-7	Output 5%	Output 20%	✓	Under voltage at bus 3 and bus 4.

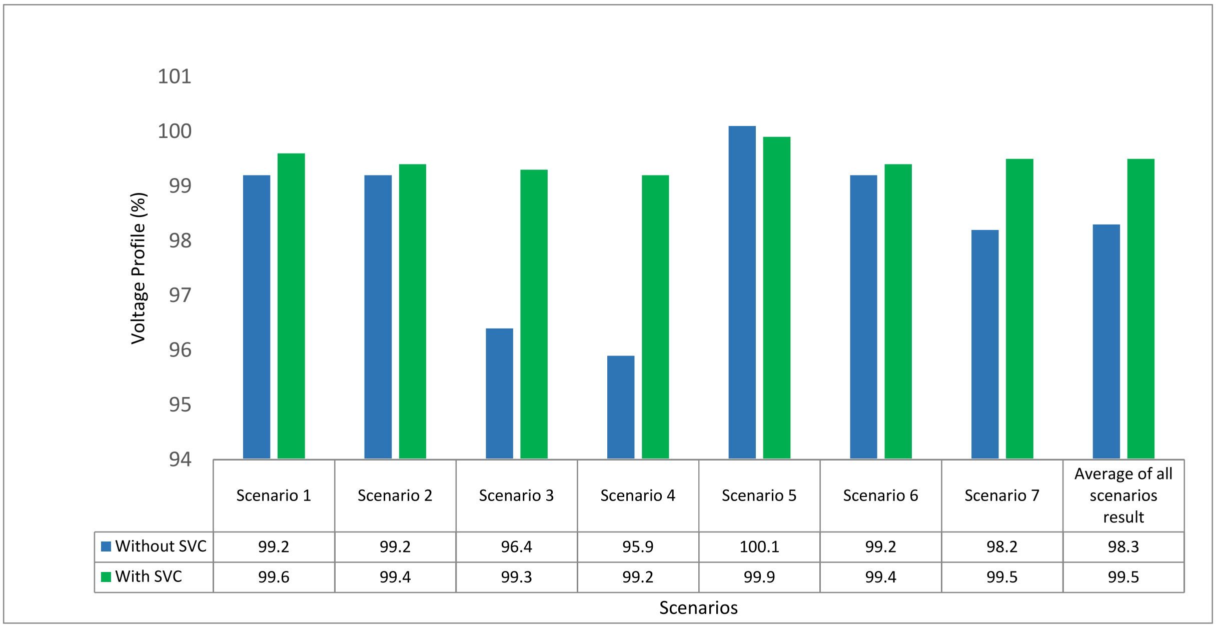


Fig. 21. Comparison of Voltage Profile (%) with & without SVC for each scenario.

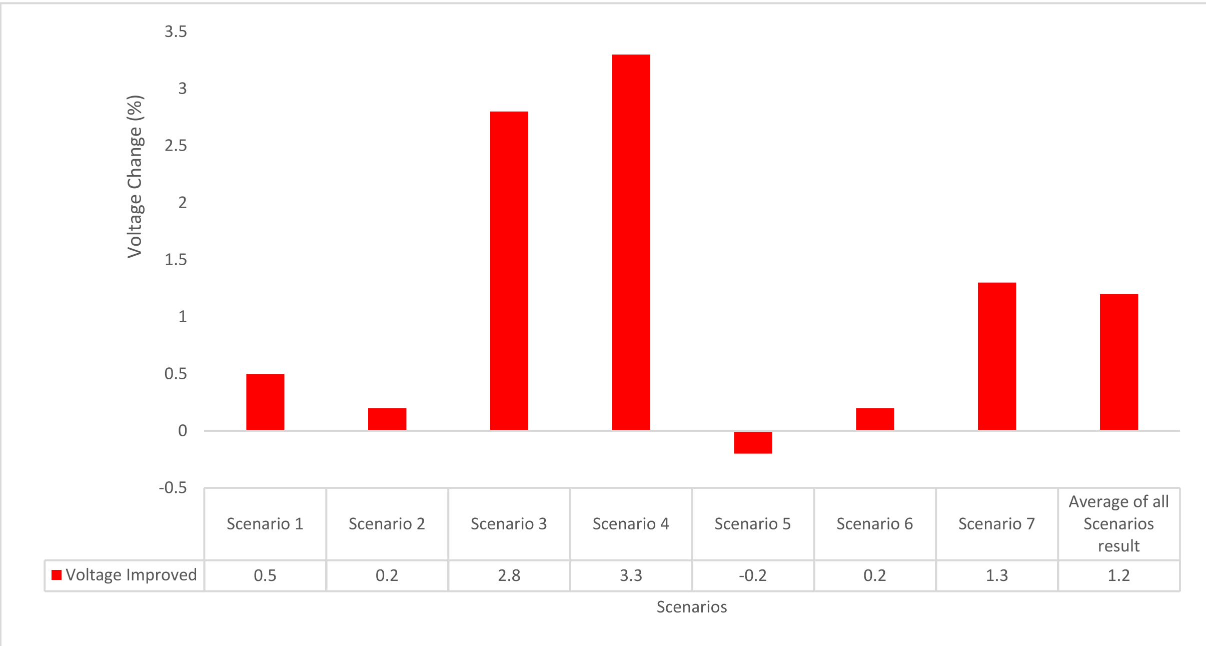


Fig. 22. Average voltage profile (%) Improvement of each scenario.

network. Two different case studies involving seven scenarios were conducted based on the source availability status and output variations. It was observed that, with the variation in the output of the power generation sources, the voltage profile of different buses changed, causing increased real and reactive power losses and reduced power transfer capacity. With the use of SVC, the average voltage profile improved by 1.12%, the power transfer capability enhanced from 314.7 kW to 317.7 kW, and the branch losses reduced by 0.94%. Moreover, the power quality improvement was found to be more pronounced during the absence of one or both of the renewable generation sources, which proves the efficiency and reliability of the proposed system. In future, a prototype model of the proposed setup can be implemented in the laboratory followed by the real life implementation at the site under study.

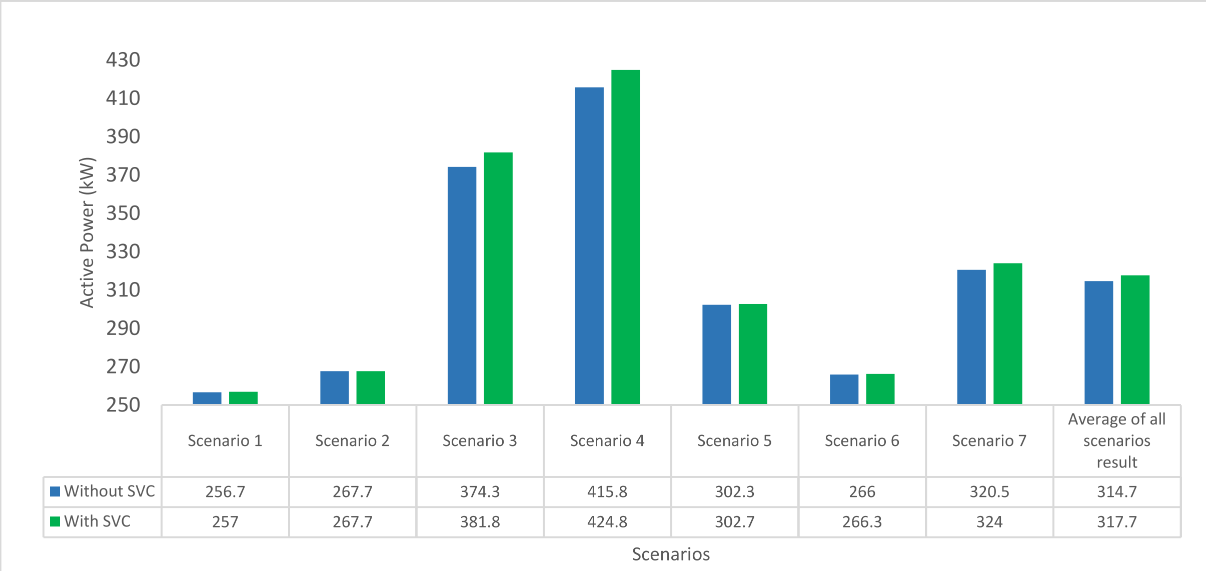


Fig. 23. Comparison of average active power (kW) transfer capability with & without SVC for each scenario.

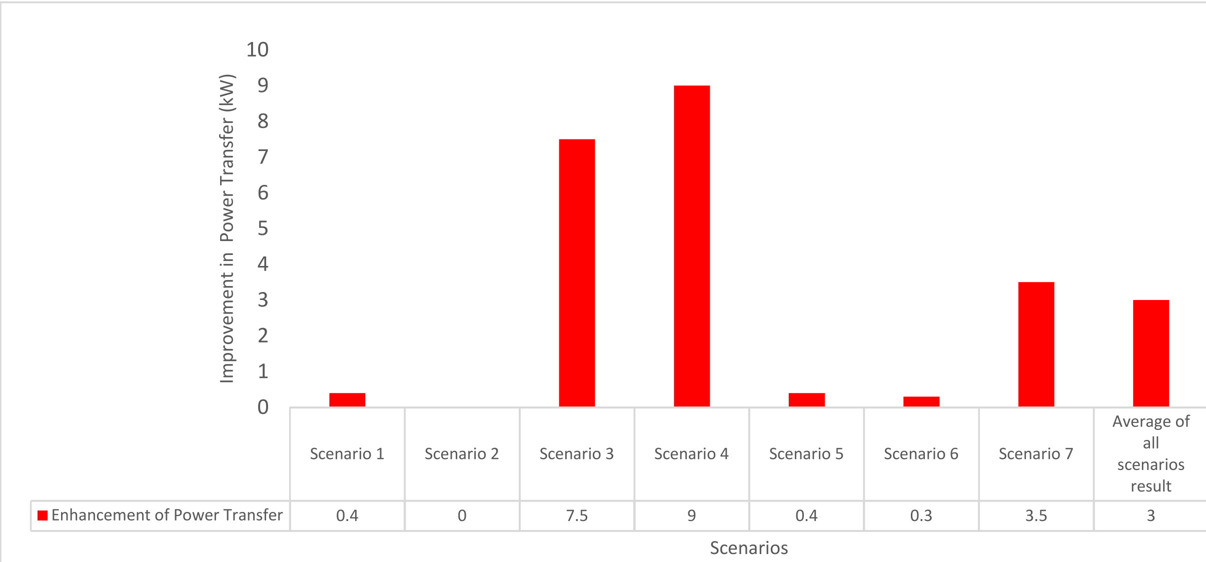


Fig. 24. Enhancement of average power transfer of all scenarios.

Author contribution statement

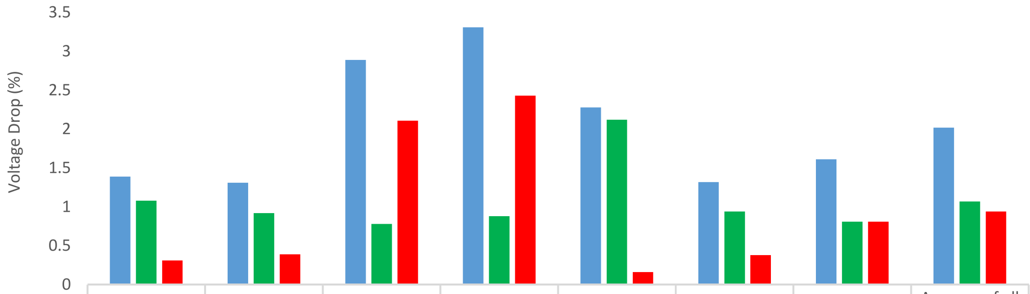
Mohammad Nurul Absar: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Md. Fokhrul Islam: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ashik Ahmed: Analyzed and interpreted the data; Wrote the paper.

Data availability statement

The data that has been used is confidential.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Average of all Scenarios result
Without SVC	1.39	1.31	2.89	3.31	2.28	1.32	1.61	2.02
With SVC	1.08	0.92	0.78	0.88	2.12	0.94	0.81	1.07
Reduced Voltage drop (%)	0.31	0.39	2.11	2.43	0.16	0.38	0.81	0.94

Scenarios

Fig. 25. Average branch losses (%) of all scenarios.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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