Impact of Distributed Generators on Voltage Stability in Transmission Network

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***Abstract*-- Due to the economic and environmental reasons, Saudi Arabia plans to deploy large scale grid-connected distributed generators (DGs) such as photovoltaic (PV) and wind energy systems. Detailed analyses must be carried out to study the impact of such systems on the dynamics and operational characteristics of the existing network. Main focus of this work is to investigate the improvement in voltage stability caused by the integration of PVs at the transmission level of a local network of Saudi Electricity Company (SEC). The effect of dynamic reactive power support from PVs during system contingency conditions to improve the network voltage profile is presented. The performance of a large scale PV system in improving the voltage stability of the network is also compared with the fast-acting reactive power compensation equipment such as static VAR compensator (SVC).**

***Index Terms*--Distributed generation, power system analysis, PV integration, reactive power compensation, voltage stability.**

I. INTRODUCTION

Electricity peak demand in Saudi Arabia is anticipated to surpass 120 GW by year 2032 [1]. To meet such high demand of electricity, Saudi Arabia plans to utilize renewable energy resources for power generation. This will ensure reduction in utilization of oil and gas resources and preservation of these hydrocarbons for the future. To decrease total dependence on oil, King Abdullah Centre for Atomic and Renewable Energy (KACARE) was established in 2010 [2]. Major task of KACARE is to conduct technical and economic analysis to introduce atomic and renewable energy in Saudi Arabia's future energy mix. KACARE has recommended gradual transformation towards renewable energy resources such that by year 2032, 54 GW will be generated through solar, wind, waste-to-energy and geothermal energy systems. To meet these targets, utility-scale solar photovoltaic (PV) systems will be deployed all over the kingdom to generate 16 GW of their share.

Grid-integration of distributed generators (DGs) such as solar PV and wind energy systems transforms the nature of the grid from conventional centralized power generation system to modern decentralized system. Such change in the grid caused by increased penetration of DGs has some technical implications on the stability and operation of the power system at both transmission and distribution levels [3-5]. Thus, their impact on system stability, especially voltage stability, must be examined thoroughly since voltage instability has been the root cause of major system collapses in recent years [6], [7].

The main cause of voltage instability is the inability of power system to meet reactive power demand, especially during heavily stressed conditions. Therefore, systems with large proportion of motor loads, e.g. Saudi Arabian residential loads, are more prone to voltage instability conditions because of substantial amount of reactive power consumption by induction motors during system contingency. Some induction motors stall and draw high reactive current when voltages drop below 85% of the nominal value, bringing further drop in voltage values [8].

High demands of reactive power for motor loads during any system disturbance can be provided by PV systems to avoid stalling of motors, which is the main focus of this work. Reactive power provision by PV systems is a well-accepted method for voltage support [9], [10]. Most power electronic converters, commonly used in grid-connected PV systems, have inherent capability of reactive power control, which can be utilized during voltage instability conditions in the system. For such practice, inverters are oversized with higher current rating e.g. they can be operated at constant power factor of 0.95 (lead-lag) [11], [12].

Main objective of this study is to investigate the impacts of grid integration of utility-scale PV systems on the voltage stability of the transmission system under line and transformer contingency conditions. Prevention of motor stalling with reactive power support from PVs is presented with dynamic simulations under multiple contingencies. Simulations were carried out in PSS/E software by Siemens PTI on the existing network of Saudi Electricity Company (SEC). Results are also compared with the scenarios when reactive power support is substantiated with static VAR compensator (SVC) devices. In addition to dynamic simulations, AC contingency analysis has also been performed with the comparison of results for all the scenarios with/without PVs and SVCs in the network.

Description of the network investigated is presented in Section II. Modeling of PV systems, SVC devices and loads is discussed in section III. In Section IV, simulation results and their analysis are illustrated. Finally, Section V presents the concluding remarks.

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II. Study Network

The Saudi Electricity Company (SEC) operates an Interconnected Transmission System for all main areas in the Kingdom of Saudi Arabia. There are four main operating areas; Central Operating Area (COA), Eastern Operating Area (EOA), Western Operating Area (WOA) and the Southern Operating Area (SOA). A summary of the Y-2014 SEC power system is given in Table-1.

TABLE 1
A summary on SEC electric power system

Item	Value (2014)	Growth
Available capacity	65,500 MW	6.5%
Peak demand	56,500 MW	7.3%
Energy sold	274,500 GWH	6.4%
110-380 kV network	59,800 circuit-km	5.1%

The study area is the part of COA with total load of 2050 MW as of the study year 2019. As shown in Figure 1, there're four 380/132 kV substations serving this area. The 132 kV lines feeding area loads are sometimes as long as 350-400 km. The area suffers from lack of reactive power compensation as there's only one SVC (-30/150 MVAr) operating for voltage support. This SVC has a limited effect under contingency conditions and was left unchanged throughout all simulation cases in this study.

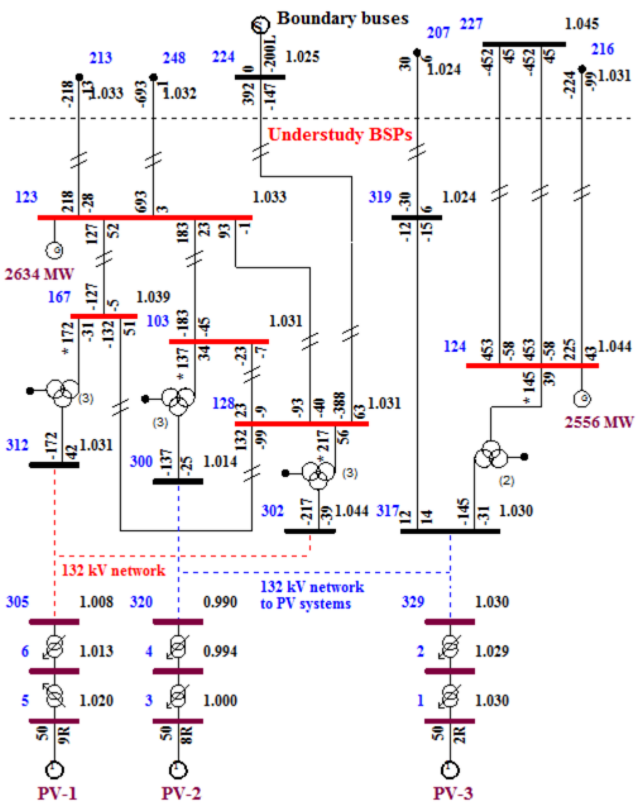

Fig. 1. Study network

III. System Modeling

A. Photovoltaic systems

In this study, photovoltaic systems were represented as wind machines in the load flow. Active power capacity of a system was set to 50 MW with the maximum reactive power provision of ±16 MVAr i.e. power factor of 0.95 (lead-lag). With these active and reactive power capacities, MVA rating of PV system was 52.5 MVA.

The dynamic modeling of photovoltaic systems was executed based on the full converter wind model "Type 4" or WT4 [13-15]. WT4 model has been developed to simulate the performance of both wind turbine generators and photovoltaic (PV) systems connected to the grid via a power converter. PV model has the added ability of simulating output changes due to solar irradiation. Main modules required to develop generic model of PV system in PSS/E are:

- PVGU1: power converter/generator module
- PVEU1: electrical control module
- PANELU1: linearized model of a panel's output curve (I-V curve)
- IRRADU1: linearized solar irradiance profile

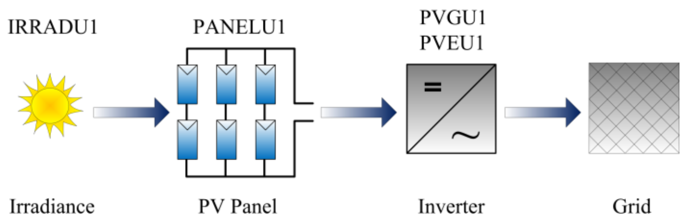

Fig. 2. Main modules of PV system modeling in PSS/E

The current injection to the grid is calculated by the power converter/generator module (PVGU1). This calculation is based on active and reactive power commands from the electrical control module (PVEU1).

The active power can be controlled by the DC power coming from the PANELU1 module, based on the irradiance level set by IRRADU1 module.

The reactive power can be controlled through any of the following options:

- Remote bus voltage control
- Power factor control
- Reactive power control

In this work, option of voltage control was employed. Parameter values used for all the modules in PV system modeling were extracted from PSS/E program application guide [13].

B. Induction motors

Induction motors representing loads in the network understudy have been modeled as type 2 CIM5 standard PSS/E induction motor model. Main parameters used were:

TABLE 2
Parameters for CIM5 model of induction motors[1]

Parameter	Value	Parameter	Value
Ra	0.04	Xa (13.8kV)[2]	0.135
Xm	4	R1	0.04
X1	0.08	R2	0.011
X2	0.055	Inertia (H)[3]	0.28

[1] All values are in pu on machine base
[2] Xa varies from 0.08 to 0.277 based on load type and voltage level.
[3] For industrial loads H=1.15

C. Static VAR compensator (SVC) devices

Static VAR Compensator (SVC) is a shunt connected VAR generator or absorber whose output is varied in order to control the specific parameters of the electric network. In this study, SVCs are employed to mitigate voltage dip problem by providing dynamic reactive power support. In PSS/E, SVCs can be modelled as either a switched shunt or a generator in the load flow [13]. In this work, they were modelled as generators just like the modelling of PV systems in the load flow. During dynamic simulations they were specified as CSVGN1 family of generator SVC models.

IV. Results and Analysis

A. AC contingency analysis

Part of the network under consideration is being supplied power through four 380/132 kV substations and many 132 kV transmission lines (overhead lines and underground cables). For AC contingency analysis, only N-1 contingencies were considered for transformers and 132 kV lines while both N-1 and N-2 contingencies were considered for 380 kV lines i.e. in total there were 68 contingencies:

TABLE 3
System Contingencies

Network component	N-1 contingencies	N-2 contingencies
380 kV lines	10	10
132 kV lines	44	-
Transformers	4	-

Criteria used to check violations in bus voltages under contingency conditions was ±10% of 1.0 pu. Overloading problems were reported for transformers and lines if flow was above 115% of rating A for transformers, above 110% and 120% of rating A for overhead lines and underground cables respectively.

Of all the contingencies, only one 132 kV line contingency caused violations in the original network. For this disturbance, many buses experienced low voltages and one 132 kV line was overloaded up to 125%. These voltage violations and overloading problems were eliminated when either PVs or SVCs were connected in the network i.e. P,Q support from PVs and Q support from SVCs improved the steady state stability of the system.

B. QV analysis

QV analysis is one of the most popular techniques to investigate voltage instability problems in the power system. In this analysis, the variation of bus voltages with respect to reactive power absorption or injection is determined by keeping the real power constant. This tool is widely used for calculating the requirements of reactive power compensation in the system to keep the voltage profile within desired operating range [6].

In this study, the optimal location of PV systems was determined after performing QV analysis for certain 132 kV buses in the area under consideration. Reactive power margin, being a useful measure of reserve, was calculated for some buses and photovoltaic systems were connected at those buses which had least margin or highest deficiency of reactive power. Reactive power margins for some buses are tabulated below:

TABLE 4
Reactive power margin

Q margin – BSPs 103 & 124		Q margin – BSPs 128 & 167	
Bus	Q (MVAr)	Bus	Q (MVAr)
329	25	305	336
320	59	310	554
325	92	308	741
300	223	304	786
317	510	302	877

Here BSP refers to bulk supply point or substation. In the above table, two groups have been made for the four BSPs supplying power to part of the SEC network under investigation. Main reason of forming two groups is that there is an interconnection at 132 kV level between BSPs 103 & 124 and BSPs 128 & 167 as depicted in Figure 3:

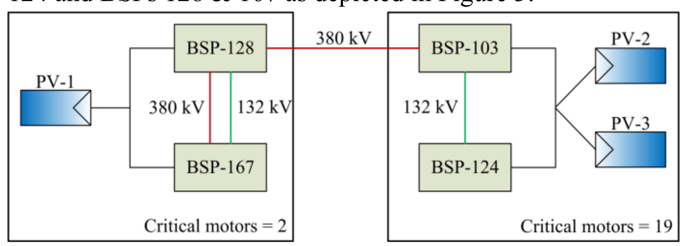

Fig. 3. BSP interconnections in the understudy area

It is apparent from Table 4 and Figure 3 that buses being fed by BSPs 103 & 124 have less reactive power margin and more critical motors as compared to the buses under BSPs 128 and 167. This formed the basis to connect two PV systems in the group of BSPs 103 & 124 and one PV system in other group of BSPs. Based on QV analysis results, PVs were connected at buses #329, 320 and 305 since these buses had least margin of reactive power in their respective group of BSPs.

The effect of integrating PVs on the reactive power margin was also analyzed. In Figure 4, QV curves are shown for the three buses with and without PV systems in the network. These QV curves were drawn for the base case without introducing any system disturbance. Reactive power margin is the MVAr distance from the lowest point (nose point) of the curve to the reactive supply curve (either Q=0 line or the curves of proposed capacitors). Reactive power margin for all three buses was increased with the integration of PVs. Q margin for buses #329, 320 and 305 increased up to 81, 253 and 355 MVAr from their previous values of 25, 59 and 336 MVAr respectively. With dynamic simulation results in the next sub-section it will be discussed how much effect these new values of Q margin have on voltage stability of the system.

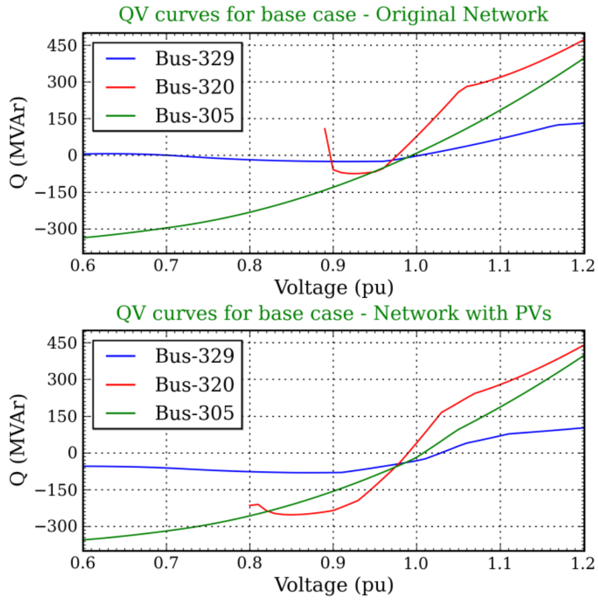

Fig. 4. QV curves with and without PV systems in the network

C. *Dynamic simulations*

a. Original network

Before the integration of PVs, multiple dynamic simulations were run for 60 seconds to assess the voltage stability of the system, especially for the under-study area. For each contingency, single line-to-ground fault was applied for 5 cycles (83.33 ms) at 380 kV buses and for 7 cycles (116.67 ms) at 132 kV buses. Fault was cleared by tripping either 1 or 2 elements, depending on the type of contingency (N-1 or N-2).

Although the investigated area did not show considerable problems in steady state in the event of transformer and line outages, voltage instability issues were observed at many buses which resulted in stalling of motors as well. An SVC with a capacity of -30/150 MVAr operating in the area also could not improve voltage profile during dynamic conditions. Motor stalling cases for all the contingencies are summarized below:

- Out of 47 motors operating in the area investigated, at least 15 were stalled for all 380 kV line contingencies (N-1 & N-2), 26 132-kV line contingencies (N-1), and 2 transformer contingencies (N-1).
- Only 2 motors were stalled for 5 132-kV line contingencies and 1 transformer contingency.
- No stalling cases were observed for 13 132-kV line contingencies and 1 transformer contingency.
- Worst contingency (BSP 103) resulted in stalling of 19 motors.
- Motor tripping at low voltages was not performed for any of the contingency conditions.

Motor speed deviation caused by the worst contingency (BSP 103) is depicted in Figure 5 (lower plot). The voltages at 380 kV bus (#103), 132 kV faulted bus (#300) and the 33 kV motor bus (#420), which is being fed by the 132 kV faulted bus, are also shown in the upper plot of the figure. When single line-to-ground fault was applied at 132 kV bus of the substation, 380 kV bus voltage almost recovered to the pre-fault value while 132 kV bus voltage became stable at less than 0.9 pu. Such low voltage value at HV (132 kV) bus results in further drop in voltage for load buses which are at low voltage level (33 kV or 13.8 kV). It is evident from the figure (upper plot) that voltage at 33 kV motor bus dropped down to 0.6 pu. Such low value at the motor bus resulted in stalling of the motor as can be seen in the lower plot.

Stalling of motors brings system voltages further down because of high current drawn by them during the voltage recovery process. Such voltage instability problems need to be avoided. It will be shown in the next sub-section that such issues can be resolved with the active and reactive power support from PV systems.

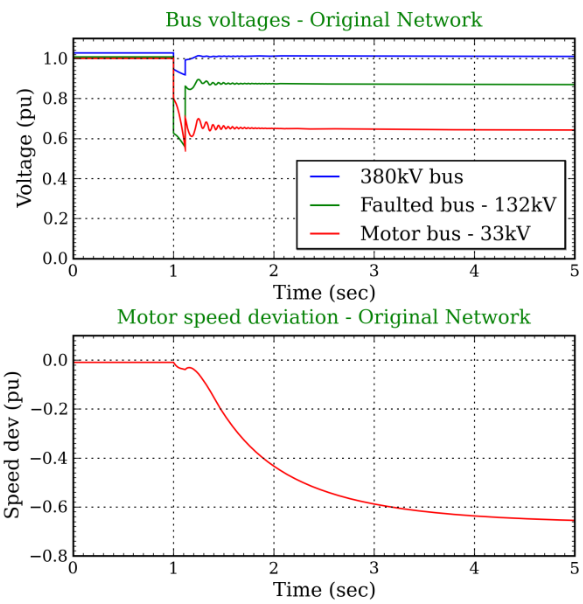

Fig. 5. Voltages at some buses under transformer contingency and motor speed deviation for the original network

b. Network with PVs

In the previous sub-section it was discussed that part of the network under investigation has reactive power deficiency due to which voltage becomes unstable when any disturbance occurs in the network. Due to inadequate resources for reactive power compensation in the area during dynamic conditions, most of the contingencies result in stalling of motors and ultimately bringing the system closer to voltage collapse condition. Components capable of providing reactive power such as PV inverters can help meeting reactive power needs in the area, also improving the voltage stability of the system. Main focus of this sub-section is to show how PVs prevent stalling of motors by providing both active and reactive power.

As described in the previous subsection (QV Analysis), three PV systems were integrated into the network at those 132 kV buses which had less margin of reactive power. Maximum active power that PVs can generate is 50 MW and they are modelled to operate within 0.95 power factor (lead-lag) i.e. maximum absorption or injection of reactive power by PVs is 16.43 MVAr.

Improvement in the system voltage profile will be discussed with the same transformer (BSP 103) contingency scenario that was presented in the previous sub-section. Voltages at the same 380 kV bus (#103), 132 kV faulted bus (#300) and the 33 kV motor bus (#420) are depicted in Figure 6. The faulted bus (#300) is directly connected to bus #320 where one of the PVs is connected. Voltage at all the three buses recovered to their pre-fault values. Since the post-fault voltage at the motor bus is more than 1.0 pu, motor did not stall this time as can be observed at the lower plot of the figure.

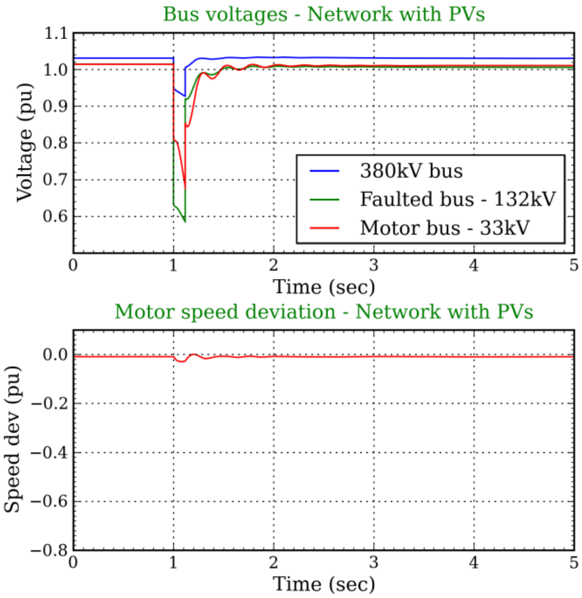

Fig. 6. Voltages at some buses under transformer contingency and motor speed deviation for the network with PV systems

Active and reactive power plots for the PV system connected at bus #320, directly connected to the 132 kV faulted bus (#300), are shown in Figure 7. As described in section III, default values were used for the irradiance model of the PV system (upper plot) i.e. for first 5 seconds, PV system generates peak active power of 50 MW (0.5 pu). Reactive power support from PV system during and after the fault is apparent from the lower plot of the figure. As shown by these plots for one of the PVs, other two PVs also provided reactive power during dynamic conditions. The proof of significant improvement in voltage stability of the system is that only 2 of the 47 motors stalled for 1 transformer contingency while motor stalling cases were not experienced for any of the other 67 contingencies (line and transformer).

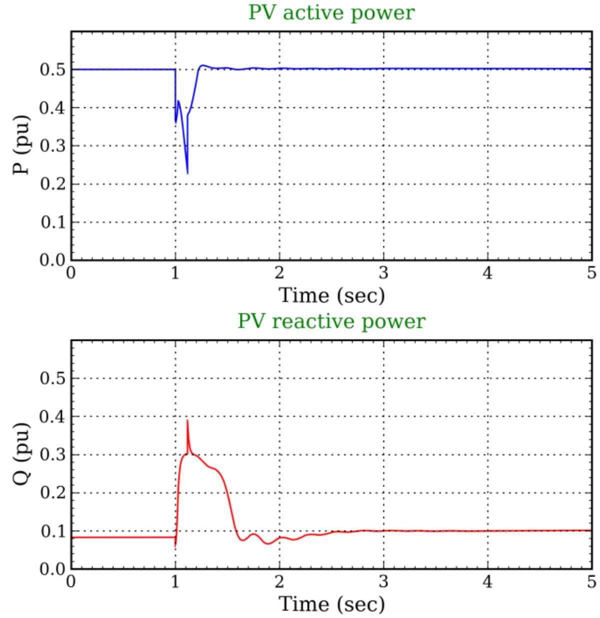

Fig. 7. Active and reactive power plot of the PV system

c. Network with SVCs

In this scenario, PVs were replaced with static VAR compensator (SVC) devices at the same locations in the network to compare the results from both PVs and SVCs. Initially the rating of SVCs was set to same value as PVs i.e. 16 MVAr and the effect of their reactive power support on system stability was analyzed. Many motors still stalled as 16 MVAr provision of reactive power from SVCs was not adequate. Due to this reason, the capacity of all three new connected SVCs was increased up to a certain size (140 MVAr) such that the motor stalling cases experienced for any of the contingencies were either none or very few. Stalling of 11 motors was experienced for SVC size of 130 MVAr while only 2 motors stalled for 140 MVAr of SVC capacity.

The scenario of same transformer contingency (BSP 103) from previous two sub-sections is used to show the response of SVCs for both ratings of 16 MVAr and 140 MVAr. Voltage at 132 kV faulted bus (#300) and 33 kV motor bus (#420) is depicted in Figure 8 for both ratings. There is a big contrast in voltage recovery at both buses with different values of reactive power support from SVCs. For 140 MVAr capacity of SVC, pre-fault and post-fault voltage at both 132 kV and 33 kV buses are same which resulted in prevention of motor stalling as well (lower plot). For 16 MVAr capacity of SVC, voltage drop at 132 kV and 33 kV buses was more than 10% and 35 % respectively. With such large values of voltage drop, motor was expected to stall as can be seen in the lower plot.

Such response of SVCs with different ratings is due to their reactive power output during the time of fault. Figure 9 shows bus voltage at which one of the three SVCs is connected (upper plot) and Q output of the connected SVC (lower plot). During the time of fault, Q support from SVC with rating of 16 MVAr was quite minimal due to which the bus voltage dropped to 0.8 pu and did not recover. When SVC rating was increased, bus voltage attained pre-fault value due to high reactive power provided by the SVC during the time of fault.

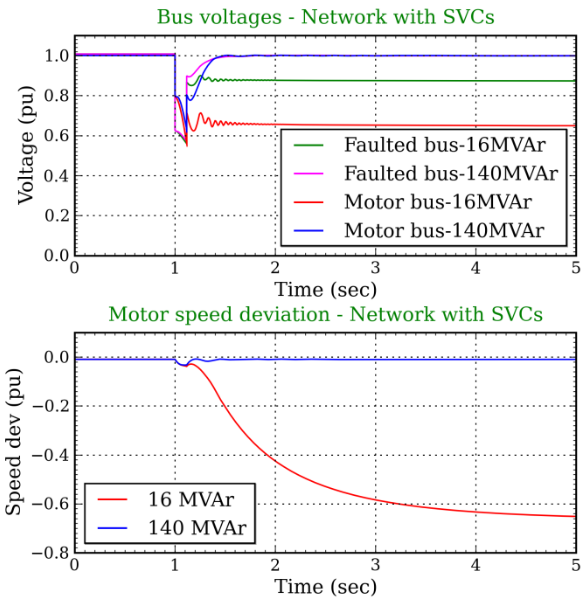

Fig. 8. Voltages at faulted (132kV) and motor (33kV) buses and motor speed deviation for SVCs with different ratings

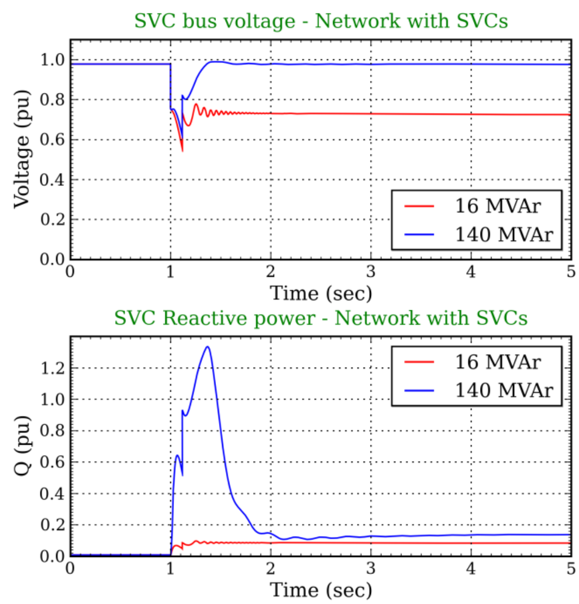

Fig. 9. Voltage at SVC bus and reactive power output for SVCs with different ratings

From figures 6-9 it is quite obvious that reactive power capacity of 16 MVAr for PV systems was adequate to prevent the stalling of most motors operating in the studied area while SVCs capacity had to be increased up to 140 MVAr to accomplish the same results. This could be attributed to the underlying technology employed by PVs and SVCs for voltage control. SVCs perform voltage regulation through thyristor-controlled reactors (TCR) and thyristor-switched capacitors (TSC). Same task of voltage regulation is carried out by PV systems through voltage source converters (VSC). During the conditions of system disturbances reactive power output of both devices decrease. This decrease is proportional to the voltage squared for thyristor-based SVCs while it is proportional to voltage for VSC-based devices such as PV system and STATCOM [16]. Another advantage of PV systems over SVCs is their fast response time which improves the power quality.

V. CONCLUSION

In this study, improvement in the voltage stability of a transmission network with the integration of photovoltaic systems is presented. Part of the central operating area (COA) from the existing network of Saudi Electricity Company (SEC) was studied. To analyze the voltage instability conditions, dynamic simulations were run without making any modifications in the network. Many motors in this area stalled during the event of single line-to-ground faults applied on the transformer or the transmission line (380 kV and 132 kV) and cleared by tripping 1 or 2 elements. To rectify these problems of motor stalling, three photovoltaic systems with the capacity of 52.5 (50±j16) MVA each were integrated in the network. Optimal placement of PVs was determined through QV analysis. P,Q support from PV systems ensured that most of the motors operating in the investigated area did not stall during dynamic conditions. Replacing the PVs with SVCs of the same reactive power size (16 MVAr) did not help solving most of the motor stalling problems. Increasing the size of each SVC to 140 MVAr resulted in only 2 cases of motor stalling as with PV systems. Less reactive power needed for voltage source converter (VSC) based PVs is due to their faster response as compared to thyristor based SVC. Also, reactive power output of the voltage source converter (VSC) is proportional to V unlike V^2 for SVC.

VI. ACKNOWLEDGMENT

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VIII. Biographies

Essam Z. Abdel-Aziz, Ph.D. He has more than 25 years of professional and academic experience in transmission system expansion and operational planning activities in major firms: Siemens-PTI and Bechtel in USA, SNC-Lavalin Inc. in Canada, Saudi Electricity Company and KFUPM in Saudi Arabia and Cairo University in Egypt. He joint SEC in March 2014 and currently, he is a consultant at the System Planning Sector.

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Rayed A. Al-Harthi was born in Taif, KSA in 1976. He received his Bachelor degree in Applied Electrical Engineering from KFUPM in KSA in February 2001. He joined the Power System Planning Department at SEC, in Jeddah, KSA in 2001 and at present, he is the manager of EHV Planning Department. His work concentrates on preparing long & medium term transmission plans and budgets for EHV Network in KSA based on technical and economic analysis.