Novel Control of Grid Connected Photovoltaic (PV) Solar Farm for Improving Transient Stability and Transmission Limits Both During Night and Day

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***Abstract*— Lack of adequate transmission capacity is a major impediment in connecting more of renewable energy sources (wind, solar) into the transmission grid. This paper presents a novel control of a grid connected photovoltaic solar farm to improve transient stability limit and hence improved power transfer capability of the transmission line. In the night, when the solar farm is completely idle, this new control technique makes the solar farm inverter behave like a STATCOM – a Flexible AC Transmission System (FACTS) device. The solar farm inverter then provides voltage regulation at the point of common coupling and improves the stability and transfer limits far beyond minimal incremental benefits. During the day also, when solar farm is producing real power, this new control strategy makes the solar farm inverter provide voltage control with the remaining inverter MVA capacity (after meeting the requirements of real power generation) and thereby increases power transfer limits substantially. Transient stability studies are performed for a realistic single machine infinite bus (SMIB) power transmission system with a PV solar farm located at the line midpoint, utilizing EMTDC/PSCAD simulation software. This paper thus presents a novel utilization of an existing solar farm asset both during night and day time to improve power transmission limits which would have otherwise required expensive additional equipment such as, series/shunt capacitors, or separate Flexible AC Transmission System (FACTS) devices.**

***Index Terms*—Photovoltaic (PV) solar power systems, inverter, voltage control, reactive power control, static synchronous compensator (STATCOM), Flexible AC Transmission System (FACTS), transmission capacity**

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I. Introduction

PHOTOVOLTAIC (PV) solar energy is one of the green energy sources which can play an important role in the program of reducing green house gas emissions. Although, the PV technology is expensive, it is receiving strong encouragement through various incentive programs globally [1], [2]. As a result, large scale solar farms are being connected to the grid. Transmission grids worldwide are presently facing challenges in integrating such large scale renewable systems (wind farms and solar farms) due to their limited power transmission capacity [3]. To increase the available power transfer limits/capacity (ATC) of existing transmission line, series compensation and various FACTS devices are being proposed [3]-[9]. In an extreme situation new lines may need to be constructed at a very high expense [10]. Cost effective techniques therefore need to be explored to increase transmission capacity. A novel research has been reported on the nighttime usage of a PV solar farm (when it is normally dormant) where a PV solar farm is utilized as a STATCOM – a Flexible AC Transmission System (FACTS) device for performing voltage control, thereby improving system performance and increasing grid connectivity of neighbouring wind farms [11, 12]. It is known that voltage control can assist in improving transient stability and power transmission limits, several shunt connected FACTS devices, such as, Static Var Compensator (SVC) and STATCOM are utilized worldwide for improving transmission capacity [13], [14].

This paper presents a novel night-time application of a PV solar farm by which the solar farm inverter is employed as a STATCOM (with its entire MVA capacity) for voltage control in order to improve power transmission capacity during nights. During day time also, the solar farm while supplying real power output is still made to operate as a STATCOM and provide voltage control using its remaining inverter MVA capacity (left after what is needed for real power generation). This day time voltage regulation is also shown to substantially enhance stability and power transfer limits. These studies are conducted on a single generator infinite bus system with a PV solar farm integrated midway in the transmission line. Three phase fault studies are conducted using the electromagnetic transient software EMTDC/PSCAD [15] and the improvement in transmission capacity evaluated both during night time and day time.

Section II describes the study system while Section III presents the results of the various fault studies during different levels of real power output from the solar farm. Section IV finally concludes the paper.

II. System Model

The single line diagram of the study system is depicted in Fig. 1. The study system comprises a large single synchronous generator (1110 MVA) supplying power over a 400 kV transmission line. A 100 MW photovoltaic solar farm is connected at the midpoint of the transmission line through a transformer at the point of common coupling (PCC). Figure 2 illustrates the block diagrams of the various subsystems in the solar farm. All the system parameters are given in the Appendix.

A. Generator and Line Models

The synchronous generator is represented in detail by a sixth order model [16] and the transmission line is represented by pi-circuits on either side of the solar farm PCC, in PSCAD.

B. Solar Farm Model

The solar farm is modeled as a voltage sourced inverter along with a pure DC source representing the solar panels. The DC power output of solar panels is fed to the DC bus to inject real power to the inverter during daytime operation, as illustrated in Fig. 2. The amount of real power injection from the solar farm to the grid depends upon the magnitude of DC input voltage. To analyze the zero real power injection (nighttime) operation the DC source is disconnected. The voltage source inverter is composed of six IGBTs in a matrix with its snubber circuits as shown by ‘IGBT matrix’ block in Fig. 2. A large size DC capacitor is used to reduce the DC side ripple. Each phase has a pair of IGBT devices which convert DC voltage into a series of variable width pulsating voltages according to the switching signal to the matrix. Switching signals are generated from the amplitude comparison of variable magnitude sinusoidal signal known as ‘modulating signal’ with high frequency fixed-magnitude triangular signal known as ‘carrier signal’ as shown in the ‘gate pulse generation’ block in Fig. 2. The variable magnitude and the phase angle of sinusoidal modulating signals are controlled by an external controller shown in ‘control system’ block in Fig. 2, which modifies the switching signal width duration. The modulating signals used for three phases are equally spaced and thereby shifted by 120^{o} whereas the same carrier wave is used for all three phases. This technique is known as sinusoidal pulse width modulation (SPWM) technique [17]. Some filter equipment may be needed at the AC side to eliminate harmonics. In this model the carrier signal amplitude is normalized to unity, hence the magnitude of modulating signal can be alternately designated as modulation index (MI) [17].

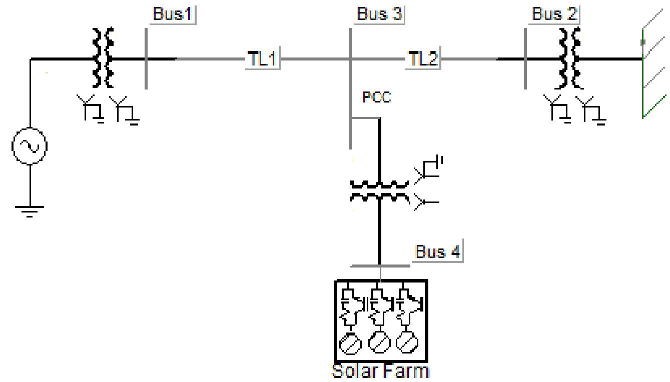


Fig. 1. Single line diagram of the study system

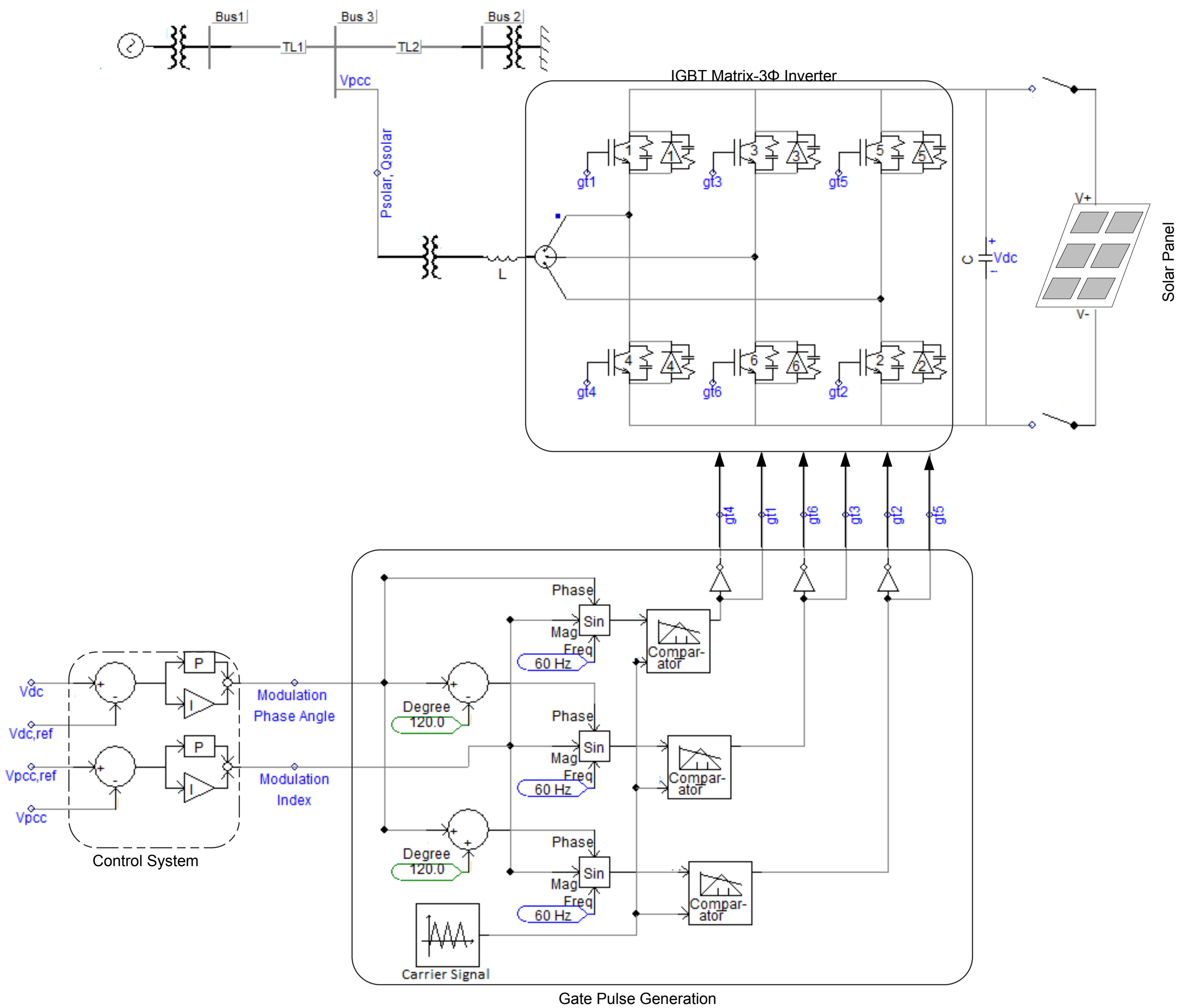


Fig. 2. Solar farm model with its corresponding blocks.

TABLE I
POWER FLOW AND VOLTAGE FOR THE SYSTEM FOR DIFFERENT SET POINT OF V_{PCC} BOTH IN NIGHTTIME AND DAYTIME

Simulation Description	Generator Bus			Middle Bus (3)				Infinite Bus	
	Pg (MW)	Qg (MVAr)	Θg (deg)	Vpcc (pu)	Θpcc (deg)	Psolar (MW)	Qsolar (MVAr)	Pinf (MW)	Qinf (MVAr)
Nighttime: No solar farm	**663**	111.6	24.28	1.017	12.40	0	0	**-644.7**	46.2
Nighttime: Solar farm with proposed voltage control at nighttime	**810**	193.0	30.21	1.000	15.42	-0.8	-31.0	**-781.0**	146.0
	777	214.0	29.25	0.990	14.94	-5.0	-93.0	**-747.5**	162.0
	812	166.0	30.00	1.010	15.36	-0.7	20.0	**-782.0**	118.0
Daytime: Solar farm without voltage control (conventional operation)	**658**	118.0	25.94	1.015	14.16	**94.0**	0	**-730.0**	80.0
Daytime: Solar farm with voltage control (proposed operation)	**694**	148.0	27.53	1.006	14.96	**94.0**	-25.5	**-764.0**	114.0
	800	189.5	30.23	1.000	15.64	**18.0**	-27.0	**-790.0**	146.0

C. Control System

In PWM switching technique, the magnitude of voltages and the angle of voltages at the inverter output are directly dependent on modulation index (MI) and modulation phase angle, respectively [17]. To control the modulation index and modulation phase angle, two separate PI control loops are integrated with the inverter, simultaneously [18]. The top PI control loop in 'control system' block of Fig. 2 controls the modulation angle to maintain the DC bus voltage, whereas the bottom PI control loop 'V controller' is used to control the modulation index according to the set point voltages at PCC. It is noted that, as the reactive power output depends upon the magnitudes of voltages at PCC and inverter terminal, therefore the reactive power flow is controlled indirectly by controlling the magnitude of voltages through modulation index in this study system.

III. SYSTEM STUDIES

All the power generated from synchronous generator and injected by the solar farm goes to the infinite bus after incurring a small amount of line losses. The criteria adopted for evaluating the increase in power transmission capacity with the proposed novel solar farm control as STATCOM is as follows. Maximum generator power output is obtained both with and without the proposed solar farm controller, both during night and day, by conducting fault studies on the study system using PSCAD/EMTDC simulation software. A 3-line to ground (3LG) fault is applied at the 400kV terminal of the generator transformer (bus 1) for 5 cycles. The maximum power flow limit is considered to be that for which the post-fault clearance settling time is within 10 seconds for the rotor mode oscillations. This results in an acceptable damping ratio higher than 5% [19]. Also, the peak overshoot of voltage at PCC is limited within 10% of its final value.

The different study results are tabulated in Table I. The maximum power transfer in the night when the solar farm is not connected to the system is 663 MW. The real power from generator P_g and that entering into the infinite bus P_{inf} for this maximum

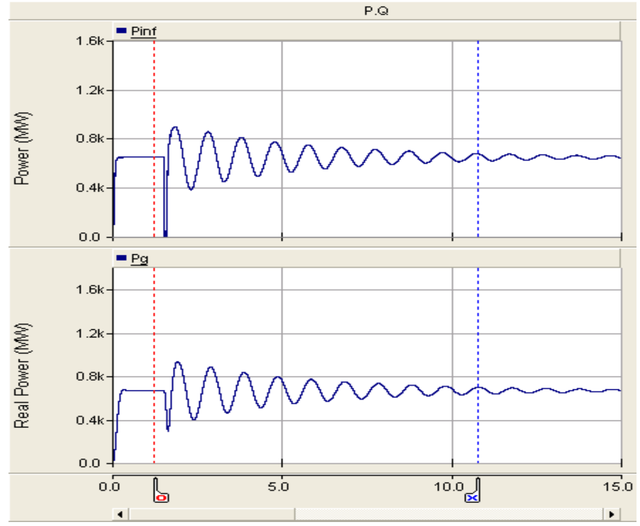
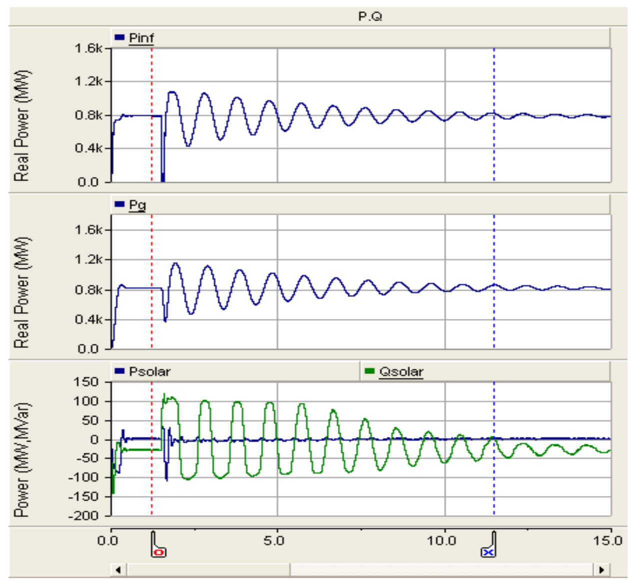
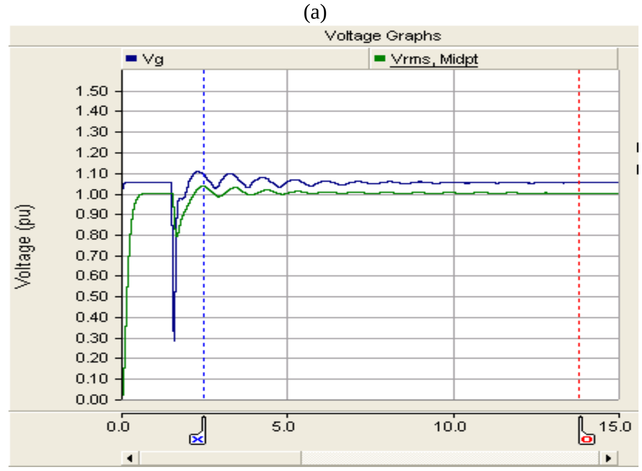


Fig. 3. Maximum nighttime power transfer from generator without solar farm.



(a)



(b)

Fig. 4. (a) Maximum nighttime power transfer from generator with solar farm (b) voltages at generator terminal and solar farm PCC

power flow are depicted in Fig. 3. Fig. 4 (a) illustrates P_g , P_{inf} ; and the solar farm real power P_{solar} and reactive power Q_{solar}. Fig. 4(b) depicts the rms voltages at the generator terminal V_g and that at the solar farm at line midpoint V_{pcc} during nighttime when the solar farm with its novel voltage controller is connected to the system. The corresponding increases in power transfer capacity are depicted in Table 1. The increase in power transfer limit is dependent upon the choice of reference values for PCC voltage $V_{pcc.}$ For instance, the power transfer limits for reference values of V_{pcc} of 0.99 pu, 1.00 pu, and 1.01 pu are 777 MW, 810 MW and 812 MW, respectively. The corresponding P_{solar} values of -5.0 MW, -0.8MW and -0.7 MW reflect the real power losses in the inverter for these cases.

It is noted from Table 1 that the level of maximum power flow from the generator depends upon the set point of PCC voltage. In the best scenario, when the V_{pcc} is regulated to 1.01 pu, the maximum power output from the generator increases to 812 MW. This demonstrates a net increase in the generator power transfer by 149 MW and a net increase in the infinite bus power by 137 MW after accounting for line losses. This significant improvement in power transmission capacity is made possible by the proposed new control of the 100 MVA solar farm which was lying idle in the night, earlier.

The increase in power transfer capacity with the new inverter voltage control is now investigated during day time, when the solar farm is supplying real power to the grid. It is emphasized that this voltage control is exercised only through the reactive power capability of the solar farm inverter. In an ideal situation when the solar farm is generating its rated real power output (100 MW, in this case study), no reactive power is available for voltage control and consequently for power transfer improvement. However, from the typical output data available from solar farms, it is seen that for almost 30-40% of the day time, the solar farm generates less than its rated power output. This implies that a finite reactive power capability is still available in the solar farm. The proposed control utilizes this remnant reactive power capacity of the solar farm to enhance the power transmission capacity, even during the day time. The maximum generator power flow limits are now ascertained for conventional operation of solar farm during day time. In this situation, solar farms inject real power at unity power factor.

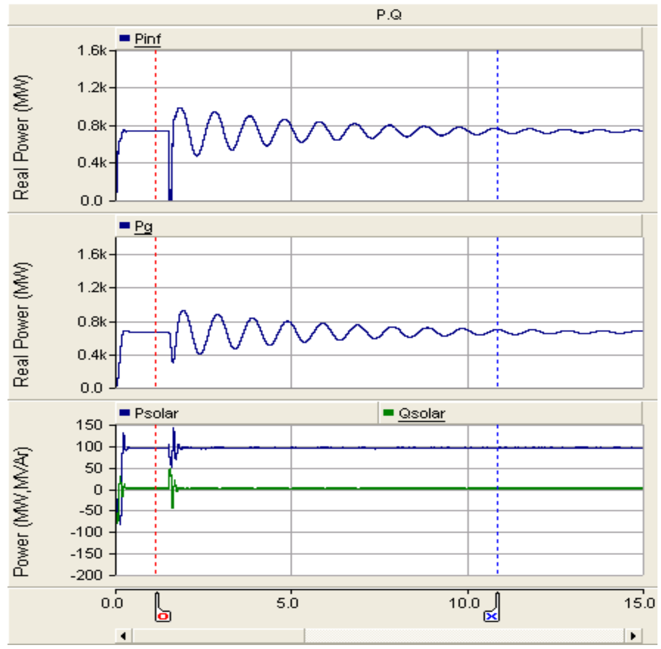
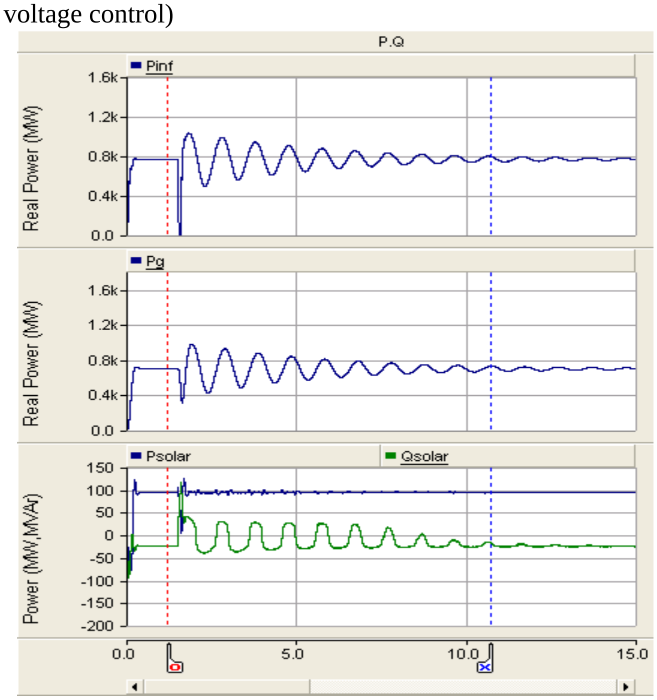
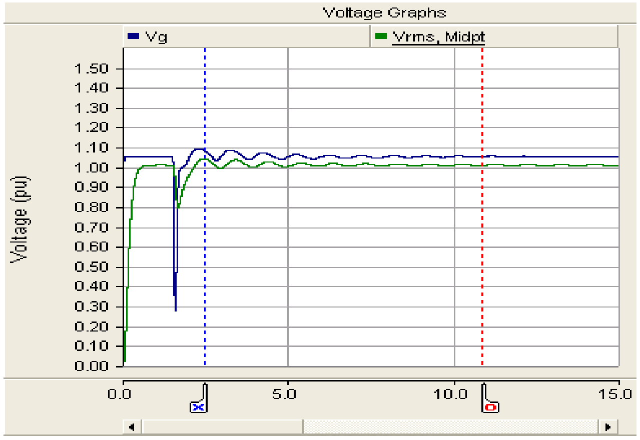


Fig. 5. Conventional connection of solar farm during day time – real power injection at unity power factor (without voltage control)



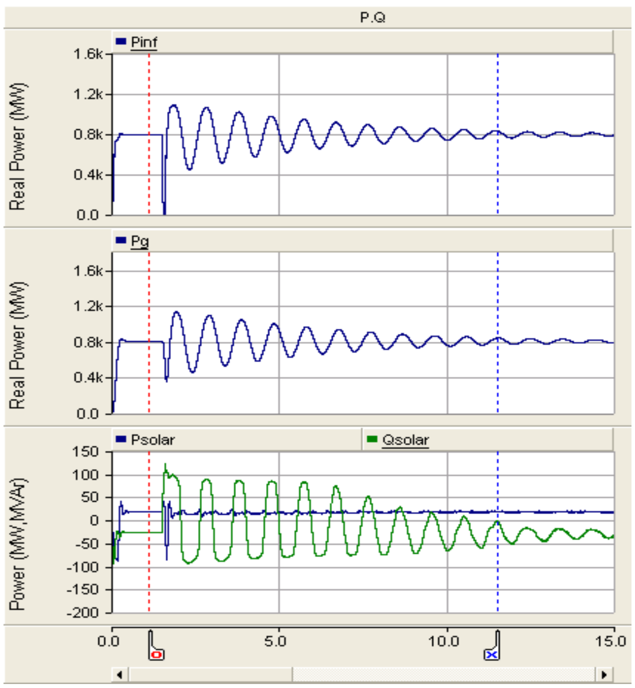
(a)

Fig. 6. (a) Maximum daytime power transfer from generator with solar farm injecting 94 MW

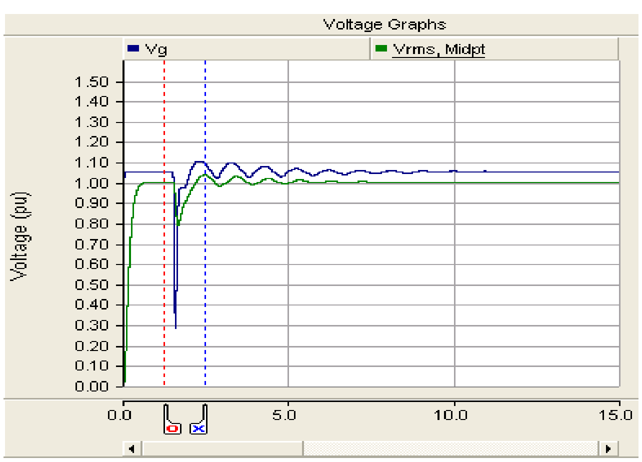


(b)

Fig. 6 (b) voltages at generator terminal and solar farm PCC



(a)



(b)

Fig. 7. (a) Maximum daytime power transfer from generator with solar farm injecting 18 MW (b) voltages at generator terminal and solar farm PCC

There is no reactive power exchange with the network nor there is any voltage regulation performed by solar farm. A high level of solar farm real power output of 94 MW is subsequently considered. Fault study is conducted for this case and P_g , $P_{inf,}$ and P_{solar} are depicted in Fig. 5. The maximum generator power flow is 658 MW and the corresponding infinite bus power is 730 MW, as shown in Table 1.

If the solar farm is made to operate with the proposed voltage control for the same real power output of 94 MW, the maximum generator power output can be increased to 694 MW i.e. by 36 MW and the infinite bus receiving end power can be enlarged to 764 MW i.e. by 34 MW. For this case, P_g , $P_{inf,}$ and P_{solar} are depicted in Fig. 6(a), whereas V_g and V_{pcc} are shown in Fig. 6(b). It may be noted that a typical solar farm operates at 94% capacity for a relatively small period of the time, and even under that scenario, the proposed voltage controller can improve power transfer capacity by 34 MW.

A case of low solar farm real power output of 18 MW is now considered. From Table 1 it is seen that the proposed voltage controller on the solar farm inverter increases the generator power output to a significantly high level of 800 MW and a corresponding receiving end power of 790 MW. For this case, P_g , $P_{inf,}$ and P_{solar} are depicted in Fig. 7(a), whereas V_g and V_{pcc} are shown in Fig. 7(b). A net increase of 60 MW is observed in the receiving end as compared to the case when the solar farm produces 94 MW at unity power factor. The novel solar farm inverter controller thus enables this additional power to be transmitted from the generator.

IV. Conclusion

This paper presents a novel control concept by which a photovoltaic solar farm is made to operate as a STATCOM – a Flexible AC Transmission System (FACTS) device and used to increase transient stability and consequently the power transfer limit of the transmission network. Three phase fault studies have been conducted on a single machine infinite bus system with a PV solar farm connected at line midpoint using PSCAD/ EMTDC simulation software. The following conclusions are made:

1) The 100 MW solar farm, which is otherwise dormant in the night, with the proposed novel control can increase the power transmission capacity (receiving end power) by 137 MW during nighttime.
2) During daytime, this solar farm can improve power transmission limits substantially even while injecting real power into the grid. At a high power output of 94 MW, the solar farm control can improve the receiving end power by 34 MW. At a low power output of 18 MW, it increases transmission capacity (receiving end power) by about 60 MW.
3) The actual increase in power transfer limits depends upon the choice of PCC voltage reference.

This study thus makes a case for relaxing present grid code to let selective inverter based renewable generators with this new control, to exercise voltage control thereby increasing much needed power transmission capability without investments in additional expensive devices such as series/ shunt capacitors and FACTS.

V. Acknowledgement

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VI. Appendix

All parameter values are all in p.u. except those indicated.

Machine/Generator:
S_n=1110MVA; V_n=22kV; f=60Hz; R_a=0.0036; x_p=0.21; T'_{d0}=6.66sec; T'_{q0}=0.44sec; T''_{d0}=0.032sec; T''_{q0}=0.057; x_d=1.933 ; x_q=1.743 ; x'_d=0.467; x'_q=1.144; x''_d=0.312; x''_q=0.312; H=3.22MWs/MVA; D=0
Transmission line:
400kV, 200 km, R=0.055Ω/phase/mi,
X_L=0.52Ω/phase/mi, B_C=5.92 X 10^{-6} Ω/phase/mi.
Transformers:
T1: S_n=1110MVA; x_l=0.15, 22kV/400kV
T2: S_n=1110MVA; x_l=0.15, 400kV/230kV
T3: S_n=100MVA; x_l=0.05, 0.208kV/400kV , Y-Y (grounded)
Inverter:
S_n =100MVA; L=0.25uH; C=320F; V_{dcref} =0.45kV; T_i = 0.0015(for both controller), K_p=10 (for modulation phase angle controller) and K_p= 1.5 (for modulation index controller).

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VIII. BIOGRAPHIES

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