Permanent Magnet Synchronous Condenser with Solid State Excitation

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Permanent Magnet Synchronous Condenser with Solid State Excitation

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***Abstract* — A typical synchronous condenser (SC) consists of a free-spinning, wound-field synchronous generator and a field excitation controller. In this paper, we propose an SC that employs a permanent magnet synchronous generator (PMSG) instead of a wound-field machine. PMSGs have the advantages of higher efficiency and reliability. In the proposed configuration, the reactive power control is achieved by a voltage converter controller connected in series to the PMSG. The controller varies the phase voltage of the PMSG and creates the same effect on the reactive power flow as that of an over- or underexcited wound-field machine. The controller's output voltage magnitude controls the amount of the reactive power produced by the SC. The phase of the controller's output is kept within a small variation from the grid voltage phase. This small phase variation is introduced so that a small amount of power can be drawn from the grid into the controller to maintain its DC bus voltage. Because the output voltage of the controller is only a fraction of the line voltage, its VA rating is only a fraction of the rating of the PMSG. The proposed scheme is shown to be effective by computer simulations.**

***Index Terms*—Synchronous condenser, permanent magnet synchronous generator, reactive power control.**

I. Introduction

Synchronous condensers (SCs) have been used traditionally in the power industry to support grids that have poor power factor and voltage regulation. Over the years, the role of SCs has been partially fulfilled by static equipment such as static synchronous compensators (STATCOMs) and static VAR compensators (SVCs) [1]. SVCs and STATCOMs have the advantage of faster responses [2]. In certain grid fault conditions [3], SCs provide higher reactive power, and, more importantly, the kinetic energy stored in the rotor provides inertial support to the grid during faults [4]. The inertial support capability and fast response time become more important as the grid-connection requirements (such as low-voltage ride-through) become more stringent. The proposed SC utilizes a permanent magnet synchronous generator (PMSG) instead of a wound-field machine. The reactive power control is achieved by a serially connected voltage converter controller rated at a fraction of the VA rating of the SC. This controller also damps the PMSG's tendency to oscillate when connected to an AC source [5]. The proposed system has a faster response than that of a traditional field-controlled SC. A crowbar circuit can be used to protect the circuit during a grid fault while the PMSG provides a surge of real power to the grid.

II. System Configuration and Theory of Operation

The proposed system consists of a voltage converter controller connected in series to a PMSG through transformers. This connection can be made in two ways, as shown in Fig. 1. Connection on the ground side has the advantage of lower operating voltage with respect to the ground and the possibility of being directly connected to the converter circuit without using transformers.

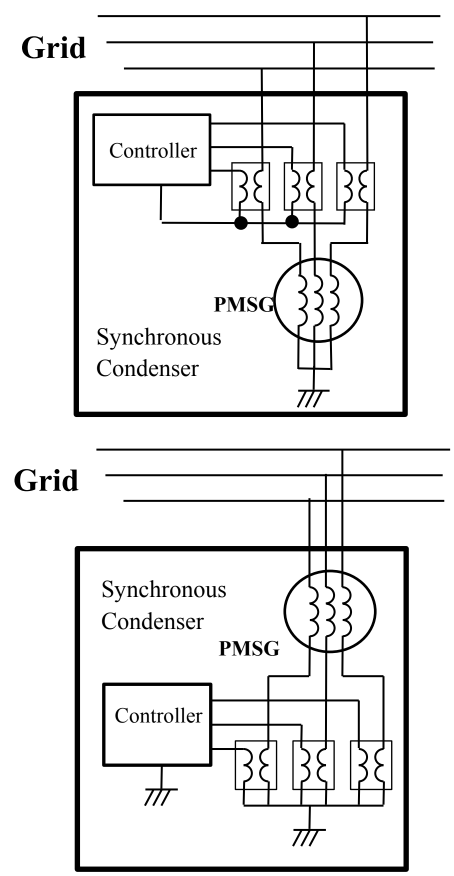

Fig. 1. Two possible configurations of the proposed system.

Fig. 2 shows the equivalent diagram of the proposed system, where V_G represents the grid voltage, V_C represents the controller's output voltage connected on the grid side of the PMSG, E represents the voltage from the internal emf of the PMSG, and X is the PMSG's impedance. The phase of the controller's output voltage, V_C, is locked to the grid voltage, V_G.

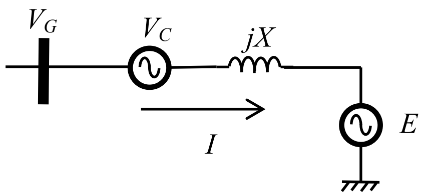

Fig. 2. Equivalent diagram of the proposed system.

As shown in Fig. 2, when the controller output voltage, Vc, is in phase with the grid voltage (V_G), the PMSG phase voltage increases. This has the effect of absorbing reactive power from the grid to the PMSG. When the output voltage is 180 degrees out of phase with the grid voltage, the PMSG phase voltage decreases, and this has the effect of delivering reactive power from PMSG to the grid. The amount of the VAR generated or absorbed is controlled by the signed magnitude of Vc. In either case, the controller does not consume any real power from the grid. The phase of Vc can be varied slightly so that the controller draws a small amount of power from the grid to maintain its internal DC bus at a certain level.

The current shown in Fig. 2 and the complex power drawn from the bus are given in (1) and (2).

$$\overline{I} = \frac{\overline{V}_G + \overline{V}_C - \overline{E}}{jX} \tag{1}$$

$$S = \overline{V}_G \cdot \overline{I}^* = \overline{V}_G \left(\frac{\overline{V}_G + \overline{V}_C - \overline{E}}{jX} \right)^* \tag{2}$$

Because V_C is controlled to be in phase with V_G (with a signed magnitude) and the PMSG has no mechanical loading, all three voltages—$\overline{V}_G$, $\overline{V}_C$, $\overline{E}$—are in phase. Also, by design the amplitude of E matches the nominal value of V_G—i.e., $V_G = E$. Under this condition, (2) can be simplified to (3). Note that the complex power S is pure reactive.

$$S = \frac{\overline{V}_G \overline{V}_C^*}{jX} \tag{3}$$

III. Reactive Power and DC Bus Voltage Control

From (3), the VAR control can be achieved with the open-loop control law in (4), where Var_{cmd} is the commanded reactive power, which can be either positive or negative (i.e., consuming VAR or producing VAR). Equation (4) is the feed-forward part of the controller.

$$V_C = \left(\frac{X}{V_G} \right) Var_{cmd} \tag{4}$$

Equation (5) is a closed-loop control law for VAR control that includes a PI controller.

$$V_C = \left(\frac{X}{V_G} \right) Var_{cmd} + \left(k_{p1} + \frac{k_{i1}}{s} \right) \left(Var_{cmd} - Var \right) \tag{5}$$

The variable V_C in (4) and (5) is the signed magnitude of the controller output voltage. The sign of V_C determines whether V_C is in phase or 180 degrees out of phase with the grid voltage, V_G.

Because the controller provides only reactive power, it consumes only a small amount of power for its operation. This power can be obtained directly from the grid via a step-down transformer and a rectifier. Another way to obtain this power is to simply vary the phase of the output voltage slightly and create a positive power flow into the DC bus of the controller. The amount of power absorbed by the controller due to the small phase shift, δ, is given in (6).

$$P = \frac{V_C^2}{X} \cdot \cos\left(\frac{\pi}{2} + \delta \right) = -\frac{V_C^2}{X} \cdot \sin(\delta) \approx -\frac{V_C^2}{X} \delta \tag{6}$$

Because only a small amount of power is required to cover the controller losses, a slight phase deviation is adequate to create the necessary real power flow into the controller to maintain the DC bus voltage of the controller. This small phase deviation does not significantly affect the requirement on the phase of V_C made earlier. Equation (7) shows the control law for the DC bus voltage, where V^*_{DC} is the reference DC bus voltage and a PI controller is used to regulate the DC bus voltage.

$$\delta = -\left(k_{p2} + \frac{k_{i2}}{s} \right) \left(V_{DC}^* - V_{DC} \right) \tag{7}$$

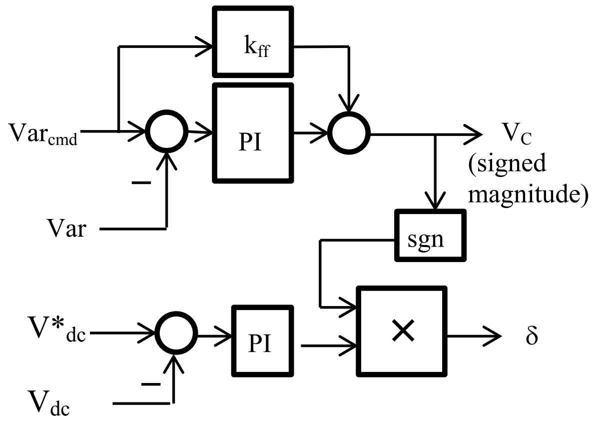

Fig. 3. Reactive and DC bus voltage controller.

Fig. 3 shows the controllers for the VAR control and DC bus voltage stabilization control. From (5), the feed-forward term k_{ff} in Fig. 3 should be as given in (8).

$$k_{ff} = \frac{X}{V_G} \tag{8}$$

Note that, as shown in Fig. 3, the sign of the phase angle output, δ, is reversed when the sign of V_C is negative. This is necessary because the reference phase used in generating the controller output voltage is always in phase with the grid voltage. When the polarity of V_C is reversed (i.e., when the condenser consumes reactive power), the phase angle, δ, should also be reversed to maintain the same power flow direction.

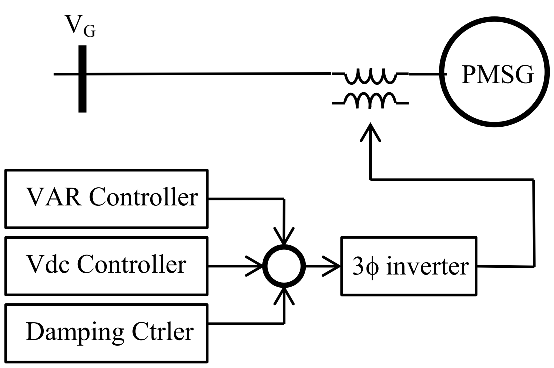

Fig. 4. Complete controller block diagram.

A PMSG tends to oscillate when connected to an AC source. At the expense of some power losses, a shorted damping winding can be incorporated into the rotor design to damp out the oscillation. The damping effect can also be achieved with a serially connected damping controller [5]. This damping controller has the same hardware configuration as the proposed SC. In fact, the control software for the proposed SC and that of the damping controller can be implemented in the same embedded controller. No additional hardware component is required. Fig. 4 shows the block diagram of the complete controller structure of the proposed SC.

IV. Simulation Results

Fig. 5 shows the top-level simulation blolck diagram of the proposed controller. The following parameters are used to generate all the simulation results presented in this section: V_G = 10 kv, V_C = 1 kv, and X = 1.5 Ω.

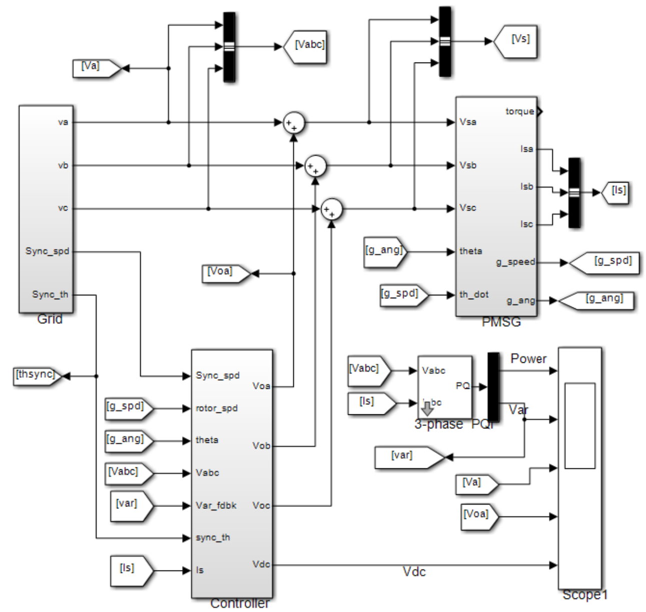

Fig. 5. Top-level simulation block diagram of the proposed PMSG-based synchronous condenser system.

Fig. 6, Fig. 7, and Fig. 8 show the results from a typical simulation run. The first (top) trace in Fig. 6 is the VAR from the synchoronous condenser (negative means supplying VAR to the grid). The second trace is the power absorbed by the synchornous condenser. In Fig. 7, the first trace shows the positive peak envelope of the Phase A grid volage. The second trace is the Phase A volage of the controller output. The last trace is the DC bus voltage. The first trace in Fig. 8 is the PMSG torque, and the bottom trace is the PMSG's electrical speed (i.e., the physical speed times the pole-pair of the machine). At 60 Hz, the electrical speed of the PMSG is $2\pi(60) = 377$ (rad/s).

The following events are simulated during this 10-s period.

0–1 s: All controller functions are disabled. The PMSG is driven by the grid voltage directly with an initial condition. As shown by the power, torque, and speed traces, the machine oscillates during this period of time. At t = 1 s, the damping function is enabled and the oscialltion is effectively damped out.

2–3 s: The VAR command is ramped to -10 MVAR (providing VAR). As shown in Fig. 6, the actual VAR follows the command closely. The VAR command levels off at -10 MVAR after t = 3 s.

Between t = 6 s and t = 8 s, the grid votlage is lowered by 5%. This is to test the effectiveness of the VAR control loop. As shown, the output VAR is maintained at the commanded value. During this period of time, the controller output is reduced by the control loop so that the PMSG's phase voltage remains the same and is unaffected by the 5% drop of the grid voltage.

The last trace in Fig. 7 shows that the DC bus voltage is maintained near the nominal value of 1.5 kv throughtout the simulation period.

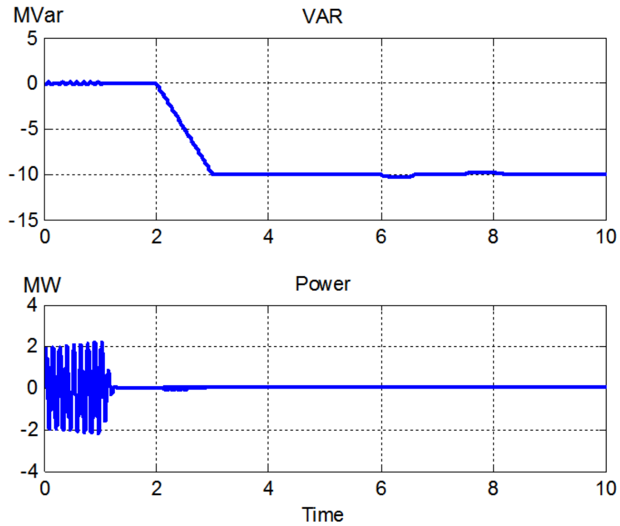

Fig. 6. (Top) VAR and (bottom) power to the PMSG.

Fig. 8 shows that the torque of the PMSG is maintained near zero and the speed of the PMSG is kept at the nominal speed throughout the simulation after the first second, when the PMSG oscillates because of the lack of damping. There are several small transient fluctuations because of the change in operating condition in the simulation.

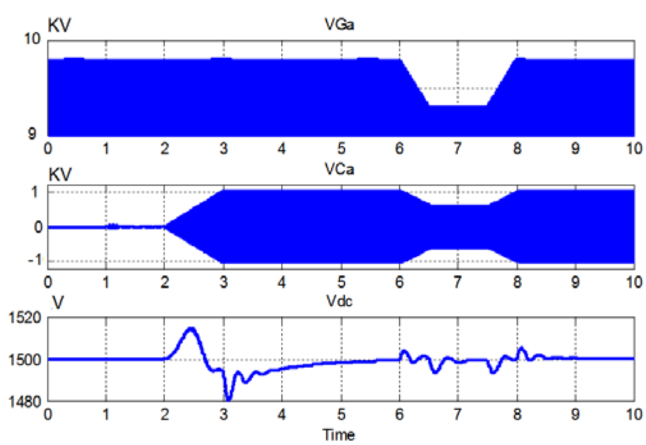

Fig. 7. (Top trace) Positive peak of the grid voltage, (middle trace) controller output, and (bottom trace) DC bus voltage.

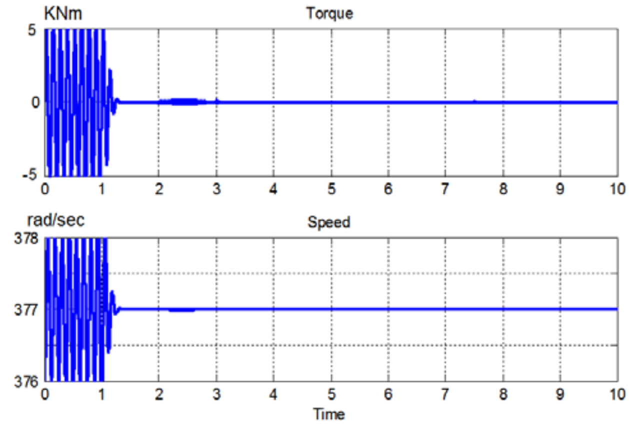

Fig. 8. (Top trace) PMSG's torque and (bottom trace) PMSG's electrical speed—i.e., the physical speed times the pole-pair of the machine.

V. Conclusion

SCs have the advantage over STATCOMs or SVCs because they are able to provide real power in a grid fault condition (provided by the rotating mass—inertial response). In this paper, we propose using PMSGs instead of wound-field machines for SCs. PMSGs are more efficient and reliable. The control of the reactive power is achieved by a serially connected voltage source controller that can react to the grid condition faster than that of a wound-field machine, and its VA rating is only a fraction of the rating of the SC. The proposed scheme is shown to be effective based on the preliminary study we have performed.

VI. Acknowledgement

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VIII. Biographies

Ping Hsu (M'1990) graduated from the University of California at Berkeley in 1988 with a Ph.D. in electrical engineering. He joined the Department of Mechanical and Industrial Engineering at the University of Illinois at Urbana-Champaign in 1989, and in 1990 he joined the Department of Electrical Engineering at San Jose State University. At San Jose State University, he served as the associate dean of the College of Engineering from 2001 to 2007 and interim dean from 2012 to 2013. His research interests include control theory, robotics, power electronics, machine control, and renewable energy systems.

Eduard Muljadi (M'82, SM'94, F'10) received his Ph.D. in electrical engineering from the University of Wisconsin at Madison. From 1988 to 1992, he taught at California State University at Fresno. In June 1992, he joined the National Renewable Energy Laboratory in Golden, Colorado. His current research interests are in the fields of electric machines, power electronics, and power systems in general with an emphasis on renewable energy applications. He is member of Eta Kappa Nu and Sigma Xi, a fellow of the Institute of Electrical and Electronics Engineers (IEEE), and an editor of the *IEEE Transactions on Energy Conversion*. He is involved in the activities of the IEEE Industry Application Society (IAS), Power Electronics Society, and Power and Energy Society (PES). He is currently a member of various committees of the IAS, and a member of the Working Group on Renewable Technologies and the Task Force on Dynamic Performance of Wind Power Generation, both of the PES. He holds two patents in power conversion for renewable energy.

Ziping Wu was born in Tianjin, China, in 1982. He received the B.E degree in thermal power engineering and M.S degree in electrical power engineering from North China Electric Power University, Beijing, China, in 2006 and 2009, respectively. After graduation, he worked as an electrical engineer in the China Electric Power Research Institute from 2009 to 2011. His work focused mainly on bulk power system modeling and simulation as well as HVDC transmission engineering. Since 2011, he has been pursuing the Ph.D. degree in the Department of Electrical and Computer Engineering, University of Denver. His current research interests include wind power generation, renewable energy, and the smart grid.

Wenzhong Gao (S'00–M'02–SM'03) received the M.S. and Ph.D. degrees in electrical and computer engineering, specializing in electric power engineering, from Georgia Institute of Technology, Atlanta, in 1999 and 2002, respectively. He is currently with the Department of Electrical and Computer Engineering, University of Denver, Colorado. His current teaching and research interests include renewable energy and distributed generation, smart grid, power system protection, power electronics applications in power systems, power system modeling and simulation, and hybrid electric propulsion systems. He is an editor for *IEEE Transactions on Sustainable Energy*. He is the general chair for the IEEE Symposium on Power Electronics and Machines in Wind Applications (PEMWA 2012).