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Power Quality Improvement of PMSG Based DG Set Feeding Three-Phase Loads

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***Abstract*-Power quality improvement of PMSG (Permanent Magnet Synchronous Generator) based on DG (Diesel Generator) set feeding three-phase loads using STATCOM (Static Compensator). A 3-leg VSC (Voltage Source Converter) with a capacitor on the DC link is used as STATCOM. The reference source currents for the system were estimated using an algorithm named as Adeline. A PWM (Pulse Width Modulation) current controller is used for generation of gating pulses of IGBTs (Insulated Gate Bipolar Transistors) of three leg VSC of the STATCOM.**

The STATCOM is able to provide voltage control, harmonics elimination, power factor improvement, load balancing and load compensation. The performance of the system was tested on various types of loads under steady state and dynamic conditions. A 3-phase induction motor with variable frequency drive is used as a prototype of diesel engine with the speed regulation. Therefore, the DG set is run at constant speed so that the frequency of supply remains constant irrespective of loading condition

***.Index Terms*-STATCOM, VSC, IGBTs, PMSG, PWM, DG Set, Power Quality**

I. INTRODUCTION

PMSGs used in WECS (Wind Energy Conversion Systems). The advancement in the field of rare earth permanent magnet with high field intensity as neodymium–iron–boron (Nd–Fe–B) has great opportunities in the field of automobile industry. These generators offer many advantages over wound field type synchronous generators such as brushless operation, no rotor winding, small size, no rotor copper losses, less maintenance and high efficiency. Because of these PMSG are also being used in turbofan jet engine electrical power generation. The main problems in PMSG were voltage and frequency control under varying load conditions. These challenges can be overcome with advancement in power converters. In WECS, the voltage and frequency of PMSG can be controlled by AC-DC-AC power converters. PMSG is compact in size so generators have potential applications in DG (Diesel Generator) set based isolated supply systems. The diesel generator sets are run at a constant speed with the diesel engine as a prime mover. There is no issue of frequency control in these supply systems. The main task in DG sets based supply systems is to maintain the constant terminal voltage. There are consistent efforts of researchers to develop methods to improve voltage regulation of PMSG based isolated supply systems. Suitable design of rotor with Nd–Fe–B magnet can reduce the voltage regulation of PMSG. Chan et. al. have presented the analysis of PMSG with Nd-Fe-B permanent-magnet rotor feeding isolated resistive load to achieve zero voltage regulation. They have presented that the inverse saliency effect of PMSG helps in improvement of voltage regulation of the generator. Chen et. al. have reported use of fixed capacitor for assisting excitation of PMSG to improve the voltage regulation and useful capacity of the generator. Rahman et.al. have regulated the terminal voltage of diesel engine drive PMSG for isolated supply system using fixed capacitor-thyristor controlled reactor. Errami et.al. have proposed variable structure direct torque control scheme for PMSG based WECS. In the research work on DG sets, very little attention has been paid to potential used of PMSG in DG sets standalone supply systems. The voltage of PMSG based DG set in isolated supply systems can be controlled using STATCOM(Static Compensator). STATCOM is widely used in grid connected and isolated supply systems such for voltage and frequency control. In addition, it can be used for load balancing, harmonics elimination, load compensation and reactive power compensation. In the proposed system with PMSG driven by diesel engine, STATCOM is used for voltage control of the PMSG. Many control algorithms are available for generation of reference source currents. Proposed system uses an Adeline based control algorithm because of its simplicity and suitability under varying load conditions.

The motivation comes from the Distributed Generation System (DGS) installed in the Renewable Energy Lab at UMass Lowell. The objective of this work is to develop universal and standardized manufacturer independent textbook model. Manufacturer specific models are more accurate and detailed, but proprietary and non-disclosure agreements become an issue for research purposes. Since wind turbines installed in the renewable energy lab are VSWT (Variable Speed Wind Turbine) with permanent magnet synchronous generator (PMSG), so such a turbine system is modeled to represent them in general. PMSG requires very less maintenance and has higher efficiency, as it doesn't have rotor current and is without a gearbox. Furthermore, there are two more advantages: firstly, it has the variable speed control capability and rotor speed can be changed in a larger range; secondly, excitation system is independent of the grid and requires another excitation source. In addition to the turbine generator, other main components of WECS are also modeled namely: wind source model, wind turbine, permanent magnet synchronous generator and AC/DC/AC control.

A. *POWER QUALITY*

Power quality determines the fitness of electrical power to consumer devices. Synchronization of the voltage frequency and phase allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electric power that drives an electrical load and the load's ability to function properly. Without the proper power, an electrical device (or load) may malfunction, fail prematurely or not operate at all. There are many ways in which electric power can be of poor quality and many more causes of such poor quality power.

The quality of electrical power may be described as a set of values of parameters, such as:

- Continuity of service
- Variation in voltage magnitude (see below)
- Transient voltages and currents
- Harmonic content in the waveforms for AC power

It is often useful to think of power quality as a compatibility problem: is the equipment connected to the grid compatible with the events on the grid, and is the power delivered by the grid, including the events, compatible with the equipment that is connected? Compatibility problems always have at least two solutions: in this case, either clean up the power, or make the equipment tougher.

B. *DISTRIBUTION GENERATION (DG)*

Distributed generation, also called on-site generation, dispersed generation, embedded generation, decentralized generation, decentralized energy or distributed energy, generates electricity from many small energy sources. Most countries generate electricity in large centralized facilities, such as fossil fuel (coal, gas powered), nuclear, large solar power plants or hydropower plants. These plants have excellent economies of scale, but usually transmit electricity long distances and negatively affect the environment. Distributed generation allows collection of energy from many sources and may give lower environmental impacts and improved security of supply.

C .GRID INTERCONNECTION

An electrical grid is an interconnected network for delivering electricity from suppliers to consumers. It consists of three main components:

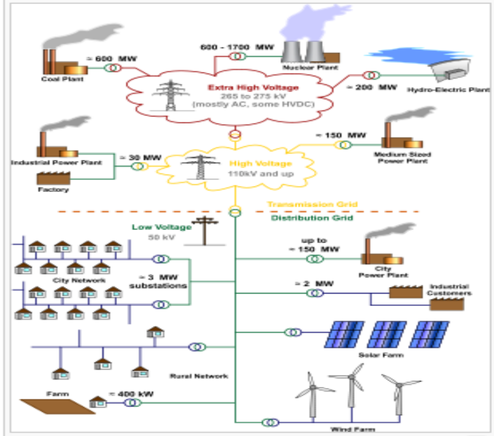
1) Generating_plants that produce electricity from combustible fuels (coal, natural gas, biomass) or non-combustible fuels (wind, solar, nuclear, hydro power).
2) Transmission lines that carry electricity from power plants to demand centers.
3) Transformers that reduce voltage so distribution lines carry power for final delivery.
4) In the power industry, *electrical grid* is a term used for an electricity network which includes the following three distinct operations:

4.1 Electricity generation - Generating plants are usually located near a source of water, and away from heavily populated areas. They are usually quite large in order to take advantage of the economies of scale. The electric power which is generated is stepped up to a higher voltage-at which it connects to the transmission network.

4.2 Electric power transmission - The transmission network will move (wheel) the power long distances-often across state lines, and sometimes across international boundaries until it reaches its wholesale customer (usually the company that owns the local distribution network).

4.3 Electricity distribution - Upon arrival at the substation, the power will be stepped down in voltage from a transmission level voltage to a distribution level voltage. As it exits the substation, it enters the distribution wiring. Finally, upon arrival at the service location, the power is stepped down again from the distribution voltage to the required service voltage(s).

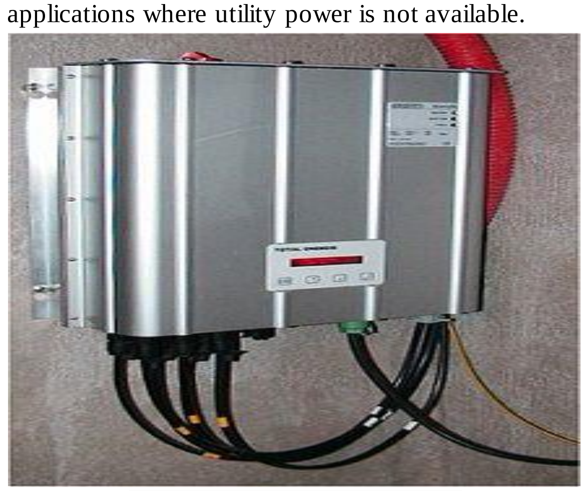
The term *grid* usually refers to a network, and should not be taken to imply a particular physical layout or breadth. Grid may also be used to refer to an entire continent's electrical network, a regional transmission network or may be used to describe a sub network such as a local utility's transmission grid or distribution grid.



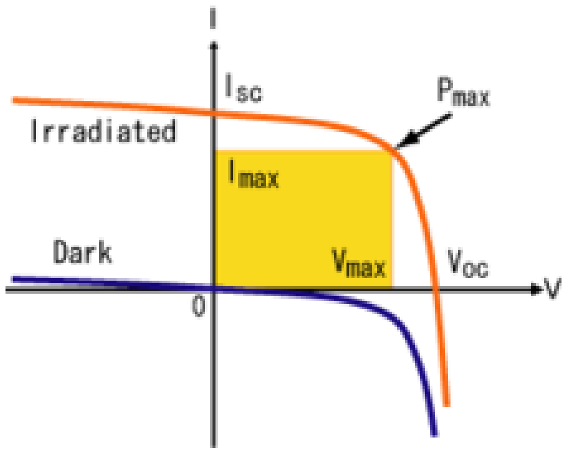
General layout of electricity networks. Voltages and depictions of electrical lines are typical for Germany and other European systems.

D. *GRID-TIED INVERTER*

A grid-tie inverter (GTI) or grid interfacing inverter is a special type of inverter that converts direct current(DC) electricity into alternating current(AC) electricity and feeds it into an existing electrical grid. GTIs are often used to convert direct current produced by many renewable energy sources, such as solar panels or small wind turbines, into the alternating current used to power homes and businesses. The technical name for a grid-tie inverter is "grid-interactive inverter". They may also be called synchronous inverters. Grid-interactive inverters typically cannot be used in standalone applications where utility power is not available.



Inverter for grid connected PV
Example of large 3-phase inverter for commercial and utility scale grid-tied PV systems



Schematic drawing of current-voltage characteristics of solar cell area of the yellow rectangle gives output power. Pmax denotes the maximum power point [Flexible AC Transmission System (FACTS)]

The ability to handle large amounts of power consequently, the use and application of this technology into electrical power systems have increased significantly. These electronic devices are based on electronic power converters and they provide the ability to make quick adjustments and to control the electrical system can be connected in series, in parallel, or in combination of both. These devices are improvement of the stability of the grid, control of the flow of active and reactive power on the grid, loss minimization, and increased grid efficiency.

II. SYSTEM CONFIGURATION

The proposed system consisting of a PMSG based DG set, a three leg VSC, and linear/nonlinear loads, is shown in Fig. A RC filter is used for filtering high frequency ripple from voltage at PCC (Point of Common Coupling). A 3-leg VSC is used a STATCOM. The VSC is connected to PCC through three interfacing inductors. The interfacing inductors connected between three legs of VSC and PCC are used to filter the high frequency ripples from current. The proposed system uses a specially designed PMSM of 3.7 kW, 50 Hz, 4-pole, 230 V.

III. CONTROL ALGORITHM

It demonstrates an Adeline control algorithm used in proposed system for estimation of reference source currents. The Adeline based control algorithm estimates amplitude of fundamental components of active and reactive components of load currents. It uses a fixed step size which may have any value from 0.1 to 1 for fast convergence. In-phase and quadrature phase unit templates are used for estimation of reference source currents.

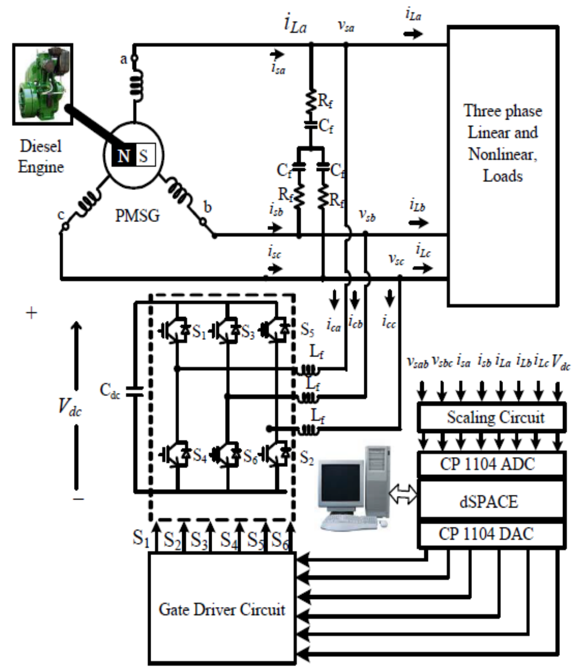


Fig. *Configuration of PMSG based DG set feeding three phase loads.*

A. *Extraction of Quadrature Phase and In-Phase Unit Templates*

In-phase unit templates are extracted by dividing instantaneous phase-voltages by amplitude of phase voltages (Vt) as,

uap=vsa/Vt, ubp=vsb/Vt,, ucp=vsc/Vt (1)

Where *vsa*, *vsb* and *vsc* are instantaneous phase-voltages which are obtained from sensed lined voltage obtained as

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix} \begin{bmatrix} v_{sab} \\ v_{sbc} \end{bmatrix} \quad (2)$$

The amplitude of phase voltages is obtained from instantaneous phase voltages as

$$V_t = \sqrt{\frac{2}{3}\left(v_{sa}^2 + v_{sb}^2 + v_{sc}^2\right)} \quad (3)$$

The quadrature unit templates are extracted using in-phase unit templates as,

$$u_{aq} = (-u_{bp} + u_{cp})/\sqrt{3} \quad (4)$$

$$u_{bq} = (3u_{ap} + u_{bp} - u_{cp})/2\sqrt{3} \quad (5)$$

$$u_{cq} = (-3u_{ap} + u_{bp} - u_{cp})/2\sqrt{3} \quad (6)$$

B. *Estimation of Active Power Component of Reference Source Current*

The Adeline minimizes the error between actual load current and its estimated weight by optimizing the weights of active and reactive components of load currents. The weight vector

for active component of load current of each phase is expressed as,

$$W_p(n) = W_p(n-1) + \mu * \{i_L(n) - \{W_p(n) * u_p(n)\}\} * u_p(n) \quad (7)$$

where, μ is fixed step size having any value from 0.1 to 1. Here the step size in proposed system is taken to be 0.2.

For a three phase system, the weight of active component of load current is given as,

$$W_p(n) = \frac{W_{ap}(n) + W_{bp}(n) + W_{cp}(n)}{3} \quad (8)$$

where *Wap(n)*, *Wbp(n)* and *Wcp(n)* are weights corresponding to active components of load currents in phase 'a', phase 'b' and phase 'c' respectively.

The weight of active power component of reference source current is obtained by adding weight vectors of (8) to the weight obtained from the output of DC link voltage PI (Proportional-Integral) controller. The input to DC link PI controller is an error voltage given as,

Vdcern) = Vdcref(n) – Vdc (n) (9)

where, *Vdc(n)* is sensed voltage on DC link voltage and *Vdcref(n)* is reference voltage of the DC link.

The output of the PI controller of DC link can be given as,

WpSTAT(n)=WpSTAT(n□1)+kpdc{Vdcer(n)–Vdcer(n–1)} +kidcVdcer(n) (10)

where, *kpdc* and *kidc* are proportional and integral gain parameters of the PI controller of DC link.

The final estimated weight of the amplitude of active power component of reference source current is given as,

$$W_{pT}(n) = W_{pSTAT}(n) + W_p(n) \quad (11)$$

The instantaneous active components of 3-phase reference source currents are obtained by multiplying weight vector of active power component and in-phase unit templates as under,

$$i^*_{sap}(n) = W_{pT}(n) * u_{ap}(n) \quad (12)$$

$$i^*_{sbp}(n) = W_{pT}(n) * u_{bp}(n) \quad (13)$$

$$i^*_{scp}(n) = W_{pT}(n) * u_{cp}(n) \quad (14)$$

C. Estimation of Reactive Power Component of Reference Source Current:

The weight vector for reactive power component of load current of each phase is given as,

$$W_q(n) = W_q(n-1) + \mu * \{i_L(n) - \{W_{qT}(n) \times u_q(n)\}\} * u_q(n) \quad (15)$$

Final weight of reactive component of load current is given as,

$$W_q(n) = \frac{W_{aq}(n) + W_{bq}(n) + W_{cq}(n)}{3} \quad (16)$$

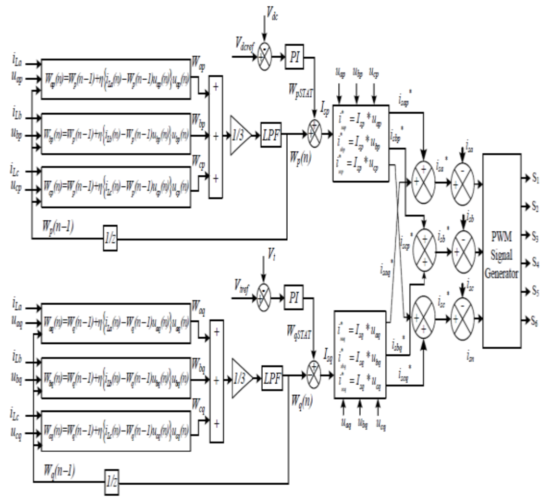
where Waq(n), Wbq(n) and Wcq(n) are weights corresponding to the reactive components of load currents in phase 'a', phase 'b' and phase 'c' respectively. The output of terminal voltage PI controller is considered weight of reactive power component of STATCOM current. The output of the terminal voltage PI controller is given as,

$$W_{qSTAT}(n) = W_{qSTAT}(n-1) + k_{pv}\{V_e(n) - V_e(n-1)\} + k_{iv}V_e(n) \quad (17)$$

where, *kpv* and *kiv* are gain parameters of terminal voltage PI controller and *Ve(n)* is error voltage. The error voltage is computed as,

$$V_e(n) = V_{tref}(n) - V_t(n) \quad (18)$$

Where, *Vtref(n)* is amplitude of reference terminal phase voltage and *Vt(n)* is the amplitude of instantaneous phase voltage at PCC.



Adeline based control algorithm for PMSG Based DG set feeding three-phase loads

The weight of reactive component of load current is subtracted from the output of terminal voltage PI controller to get the weight vector of reference source current as,

$$W_{qT}(n) = W_{qSTAT}(n) - W_q(n) \quad (19)$$

The instantaneous reactive components of three phase reference source currents are obtained weight of reference source current and quadrature phase unit templates as,

$$i^*_{saq}(n) = W_{qT}(n) * u_{aq}(n) \quad (20)$$

$$i^*_{sbq}(n) = W_{qT}(n) * u_{bq}(n) \quad (21)$$

$$i^*_{scq}(n) = W_{qT}(n) * u_{cq}(n) \quad (22)$$

D. Estimation of Reference Source Currents:

The instantaneous reference source currents are obtained by adding instantaneous active and reactive power components of reference source currents as under,

$$i^*_{sa} = i^*_{sap} + i^*_{saq},\ i^*_{sb} = i^*_{sbp} + i^*_{sbq},\ i^*_{sc} = i^*_{scp} + i^*_{scq} \quad (23)$$

The estimated reference source currents and sensed source currents are compared with each other and error is given to the PWM current controller to generate gating pulses for IGBTs (Insulated Gate Bipolar Transistors) of VSC of STATCOM.

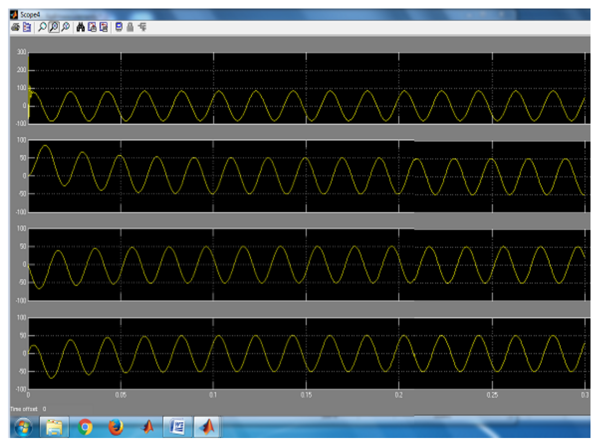
IV. RESULT AND DISCUSSION

Performance of the system is analyzed under linear and nonlinear loads at steady state and transient conditions. Linear load is a simple RL type load. The nonlinear load is realized by using a three phase rectifier with a resistance on DC link. An inductor is also connected in series with resistance to inject harmonics in current on ac input. The performance at linear and nonlinear loads is also given here.

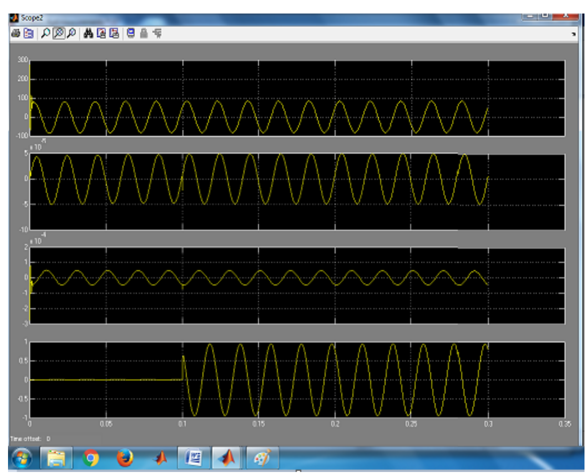
A. *Performance of DG System under Linear Loads*

The performance of the PMSG based DG set under linear load is demonstrated in Fig. The system is subjected to three phase load with at displacement power factor of 0.99.

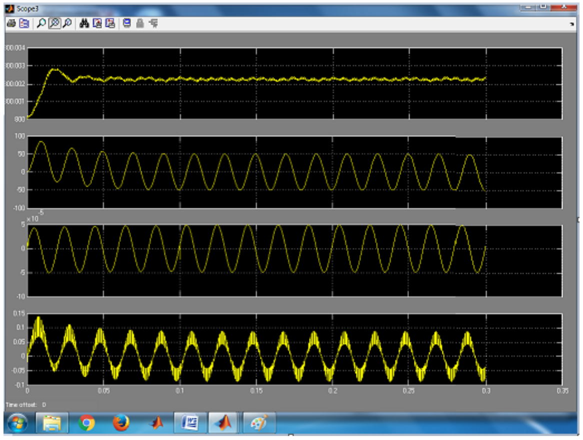
The dynamic performance of the system under the transient condition is demonstrated in Fig. below



(a) $v_{sab}, i_{sa}, i_{sb}, i_{sc}$



(b) $v_{sab}, i_{La}, i_{Lb}, i_{Lc}$



(C) $v_{dc}, i_{sa}, i_{La}, i_{Ca}$

The system is subjected to three phase load with displacement power factor . Initially, the system is subjected to unbalanced load by removing the load from phase'c'. The dynamic performance of system is tested by changing the load from unbalanced to balance by inserting the load. It can be observed from these waveforms that system is able to overcome the transient within couple of cycles. It is also observed the DC link voltage has slight oscillatory under unbalanced condition and has under shoot during transient. The DC link capacitor supplies the energy stored to meet the additional load demand during the transient period.

B. Performance of DG System Under Nonlinear Loads:

The performance of the system under nonlinear load is illustrated in Fig.

However, the speed control mechanism of prototype of the diesel engine is able to maintain the frequency of the supply almost at 50 Hz with small variation of ±0.2 %.

Therefore, the proposed PMSG based DG set along with STATCOM can be used for feeding linear and nonlinear balanced and unbalanced loads. The proposed PMSG based DG set has also inherent advantages of low maintenance, high efficiency and rugged construction over a conventional wound field synchronous generator based DG set.

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