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An Overview of Applications of DSTATCOM

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Abstract

Distribution STATic COMpensator (DSTATCOM) is used to mitigate many current quality problems like harmonics elimination, power factor correction, load balancing, noise cancellation and voltage quality problems like sag, swells, impulses, voltage unbalances, fluctuations. Many research papers have been critically studied and applications of DSTATCOM are classified into suitable categories. Typical applications in these categories are presented in this paper.

Keywords: DSTATCOM, VSI, SRF, PSO

INTRODUCTION

In present day distribution systems, major power consumption has been in reactive loads, such as induction motors used in industrial, commercial and domestic sectors. These loads draw currents at lagging power-factor and therefore gives rise to reactive power burden in the distribution system. Whenever there is an increase in large inductive load, line current increases causing increase in line voltage drop and power loss. This causes a decrease in bus voltage. As other loads connected on the same bus get lower voltage, their performance is affected. Hence it is necessary to maintain the bus voltage constant.

Excessive reactive power demand increases feeder losses and reduces active power flow capability of the distribution system whereas unbalancing in loads affects the operation of transformers and generators [1]. A DSTATCOM can be used for compensation of reactive power and unbalanced loading in the distribution system. The new technologies in solid state devices and their use in control of equipment have led to the power quality (PQ) problems. PQ problems are of major concern in the distribution system which leads to decrease in efficiency of the system and a serious attention is to be given to the increase in pollution of distribution systems. The ever increasing deployment of nonlinear loads such as solid state power converters in medical equipment, fluorescent lighting, renewable energy systems, office and household equipment, arc furnaces, high frequency transformers, etc. inject harmonics into the system and decrease the quality of power. Moreover, due to unbalanced three phase or single phase loads, the nature of voltage waveforms in the distribution system is distorted which eventually affects the performance of equipment. DSTATCOM has been used to mitigate many PQ problems like harmonic pollution power factor correction, load balancing, noise cancellation, sag, swells, impulses, unbalances and fluctuations in voltage.

This paper presents a comprehensive review of different applications of DSTATCOM. Many research papers have been consulted and the applications are classified into four categories: 1. Harmonic reduction; 2. Voltage control; 3. Load balancing; and 4. Reactive power compensation.

PRINCIPLE OF OPERATION OF DSTATCOM

DSTATCOM is a 3-phase, multilevel IGBT based voltage source inverter connected to load bus through a shunt transformer (refer Fig. 1.), represented by X which is per phase value of equivalent reactance of shunt transformer connecting DSTATCOM to the point of common coupling (PCC) and R represents total loss in the inverter and coupling transformer.

The real power exchange between the DSTATCOM and PCC is governed by phase angle between the inverter output fundamental voltage and PCC voltage. This real power supplies the losses in the DSTATCOM circuit. The reactive power exchange is determined by difference in amplitude between the inverter and PCC voltages which results in the voltage compensation at the PCC.

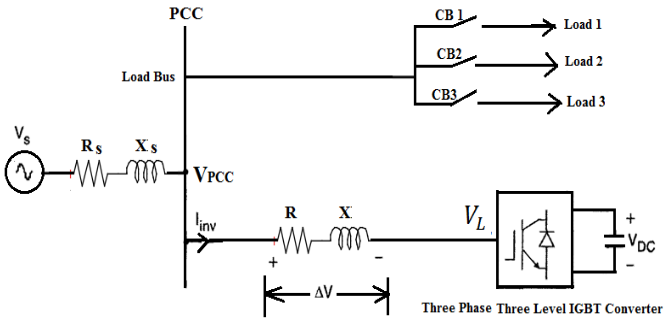


Figure 1: Single line Diagram of 3-phase, multilevel VSI based DSTATCOM

Fig. 2(a) and Fig. 2 (b) show the phasor representation at the fundamental frequency for leading and lagging VAr compensation respectively[2].

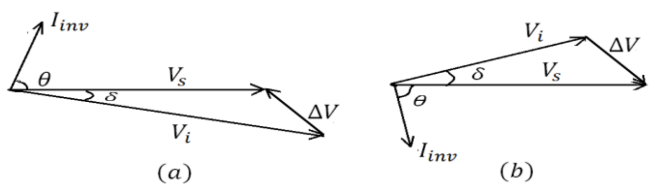


Figure 2: Phasor representation of VAR compensation (a) Leading VAR Compensation (b) Lagging VAR Compensation

When an inductive load on supply system increases, the load voltage decreases. The DSTATCOM senses this decrease of voltage and supplies capacitive reactive power to the load bus so that voltage across load is brought closer to the nominal value depending on the power rating of DSTATCOM.

Referring to Fig.2(a), the VSI output fundamental voltage V_i lags A.C. source voltage V_s by angle δ and the inverter output current I_i lags the voltage drop across the reactor (ΔV) by nearly 90 deg. since R << X. Active power flows from PCC to VSI at lagging δ whereas I_i is leading V_{pcc} by an angle θ.

When a capacitive load is switched on, there is an increase in load voltage which is sensed by DSTATCOM and it absorbs reactive power thereby maintaining load voltage closer to the nominal value.

Referring to Fig. 2(b), the VSI output fundamental voltage V_i leads PCC voltage V_{pcc} by angle δ and the inverter output current I_i leads the voltage drop across the reactor (ΔV) by nearly 90 deg. since R << X. Active power flows from PCC to VSC at leading δ. Ii is lagging V_{pcc} by an angle θ.

LITERATURE SURVEY

Various PQ problems such as poor voltage regulation, harmonics, load balancing, poor power factor, excessive neutral current, voltage flicker, voltage sag and swell are of common occurrence due to the voltage injected by the wind generators into grid. These problems have been tackled by various researchers [3-14]. Many predictive current control strategies are proposed for DSTATCOM to improve power quality in distribution system [15-34]. Use of DSTATCOM to control voltage in distribution system in an interactive manner is contributed by various researchers [35-60]. Compensation of harmonics in smart grids is dealt in [61]. A practical control strategy provided through a distributed control mode by using more than one DSTATCOM is proposed in [62]. The control of a synchronous reluctance generator (SYRG) driven by a biogas biomass diesel engine as a prime mover in a distributed Power Generating system is reported in [63]. Various researchers have proposed a coordinated control of distributed generators (DGs) and DSTATCOM in a microgrid [64-81]. Many other researchers have worked in the areas of microgrid and converter interfaced micro sources [82-98]. Reactive compensation in distribution network is also studied by various researchers [99-105].

APPLICATIONS OF DSTATCOM

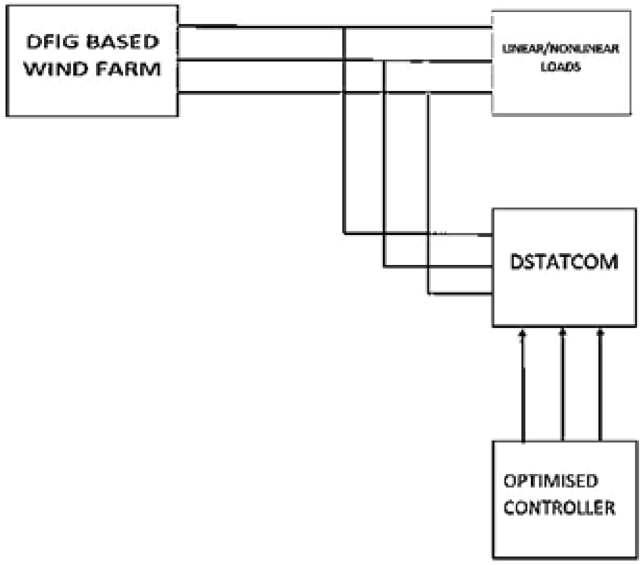
This is classified into following categories-

1. Harmonic reduction;
2. Voltage control;
3. Load balancing and
4. Reactive power compensation

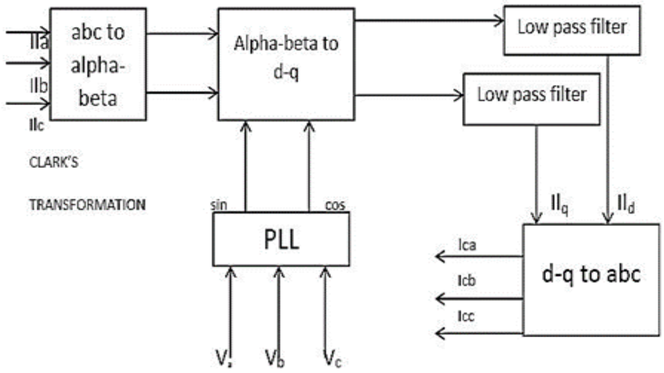
1. HARMONIC REDUCTION

A) Wind Farm

When wind generators are connected to grid, various power quality problems such as poor voltage regulation, harmonics, load balancing, poor power factor, excessive neutral current, voltage flicker, voltage sag and swell are of common occurrence. These lead to serious problems such as system frequency oscillations and change in power line capability. To minimize these effects a DSTATCOM with wind farm [3] is shown in Fig. 3(a).The DFIG based wind farm is operating in the islanding mode. A Synchronous Reference Frame (SRF) based technique (ref. Fig. 3(b)) is employed and the gains of PI controller are optimized using Particle Swarm Optimization (PSO) technique.



(a)



(b)

Figure 3. DSTATCOM with wind farm (a) Schematic diagram of the system, (b) Block diagram of SRF technique

A flow chart of PSO is shown in Fig. 4. PSO algorithm works by having a population (called a swarm) of candidate solutions (called particles). These particles are moved around in the search-space according to a few simple formulae. It is a population based optimization technique. Each particle keeps track of its coordinates in the problem space which are associated with the best solution (fitness) that has been achieved so far. This is called the p_{best}. The PSO concept consists of changing the velocity of each particle towards its p_{best} and g_{best} .

Initially a population of random solutions is considered. Each particle is assigned a random velocity with which they start flying in the search space. The previous best position of the particles are kept in memory by each particle. This previous best value is known as p_{best}. The fundamental concept behind this technique is that the particles always follow their respective p_{best} and g_{best} positions at each time.

The performance of the DSTATCOM depends on the proper tuning of the controllers. A detailed knowledge of the complex mathematical model of the system is required to determine the values of the control parameters accurately. In order to simplify this process computational control techniques are applied. The conventional PI controllers are tuned at a particular operating condition. It may not work well when the operating point changes. To overcome the problem the gains of the PI controller are optimized by PSO. PSO technique is being used to determine the optimal parameters of the two PI controllers in the current control and voltage control blocks. To determine the optimum control parameters with the help of PSO, the four control parameters of PI controllers K_{p1}, K_{p2}, K_{i1} and K_{i2} are considered as four dimensions of the swarm.

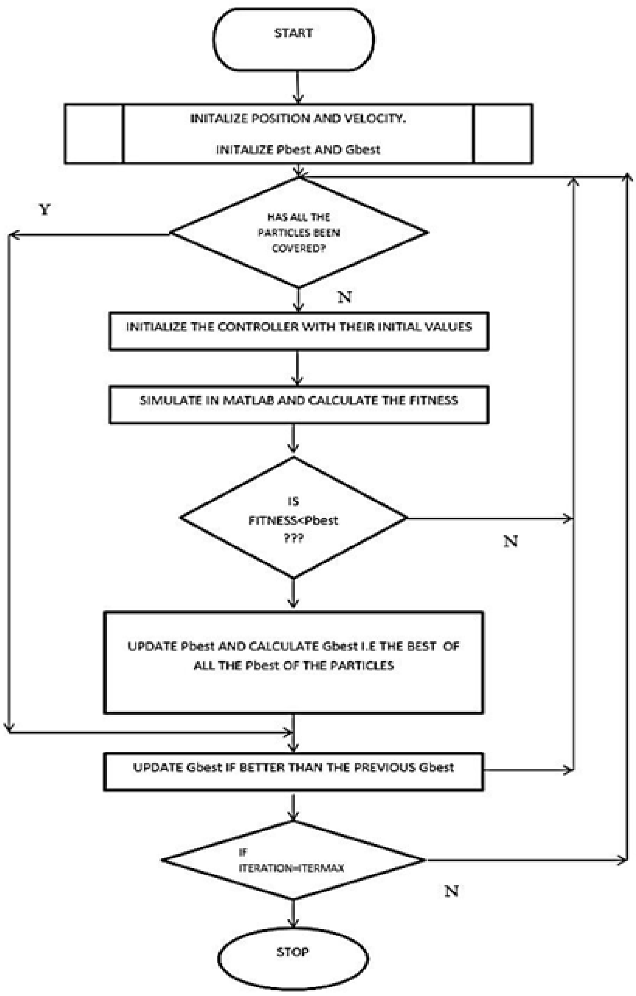


Figure 4. Flow chart of PSO

Simulation study of the model with linear and nonlinear loads [3] has shown that introduction of DSTATCOM minimizes the injection of voltage harmonics injected in the system. In case of non-linear loads voltage THD without DSTATCOM is found to be 154.6% and with optimized DSTATCOM 19.33%.

B) Predictive Current Control of DSTATCOM

Many predictive current control strategies are proposed for DSTATCOM to improve power quality in distribution system [15-34]. Unlike classical control schemes, the proposed method [15] neither requires current PI controllers nor modulators at switching signal generation stage. The discrete-time model of the converter, filter and terminal voltage are used to predict the future behavior of the compensating currents for each of the eight possible switching states. The control method decides a switching state in which the actual currents are closer to their references. Fig.5 shows the basic control structure of proposed control strategy which consists of one positive sequenced detector, low pass filters (LPF1 and LPF2) and arithmetic calculators. The average power is obtained by filtering instantaneous power p_{inst} through LPF2. LPF1 is used to extract the fundamental from distorted voltage at PCC.

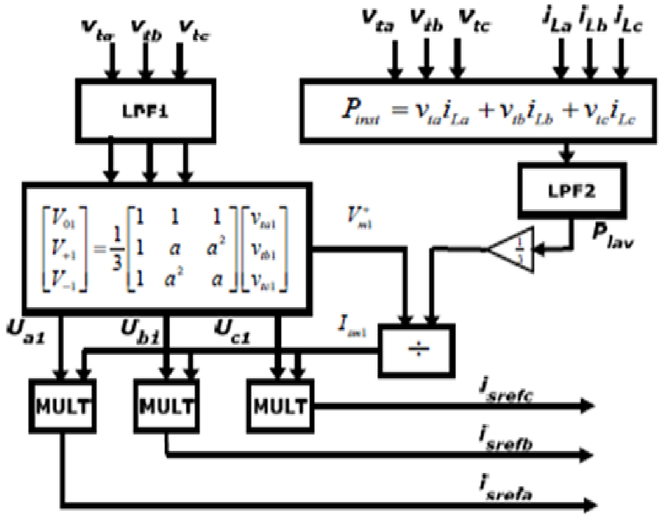


Figure 5. Control structure of proposed controller [15]

The performance of the proposed controller is evaluated based on three different cases.

- Case1- Balanced Source and balanced Non-Linear load
- Case2- Balanced Source and Unbalanced Non-linear load.
- Case3- Balanced distorted Source and Unbalanced Non-linear load.

With this control scheme it has been found that THD of load compensation is well within the allowable range of IEEE standards (5% maximum) with achievement of unity P.F. Table I presents comparative analysis of source current THDs for three different types of controllers.

Table I. Comparative Analysis of source current THD (%) after compensation

Control scheme	THD(%) of source current after Compensation		
	CASE – 1	CASE -2	CASE - 3
Hysteresis Current Controller	4.3274	3.8259	4.6367
Sliding mode Controller	4.1498	4.2282	4.5536
Model predictive Controller	3.2956	3.6011	4.1023

This predictive control offers several advantages such as 1) As there is no need of modulation, signal can be implemented directly; 2) constraints can be included directly in the cost function, 3) Switching frequency is controllable, 4) predictive control can be applied to variety of systems, and 5) non-linearities can be easily incorporated in the control system.

2. VOLTAGE CONTROL

A) Interactive DSTATCOM

Use of DSTATCOM to control voltage in distribution system in an interactive manner is contributed by various researchers [35-60].

DSTATCOM has two modes of operation, namely current control mode (CCM) and voltage control mode (VCM). Interactive DSTATCOM provides smooth transfer of modes of operation while remaining connected in the distribution system [35].

In normal operation, the interactive DSTATCOM operates in current control mode (CCM) to keep the source currents balanced, sinusoidal, and at a unity power factor. During voltage disturbances, the CCM operation cannot improve load voltage. In that case, DSTATCOM operation is changed to voltage control mode(VCM), which maintains a constant voltage across the sensitive loads such as computers, T.Vs. etc. Hence, the interactive DSTATCOM ensures continuous, flexible, and robust operation of the load. Predictive control algorithms for CCM as well as VCM operation are developed for fast operation during mode transfers. The filter current requirements are very much reduced in this scheme with reduction of losses in the filter and feeder and improvement in inverter efficiency.

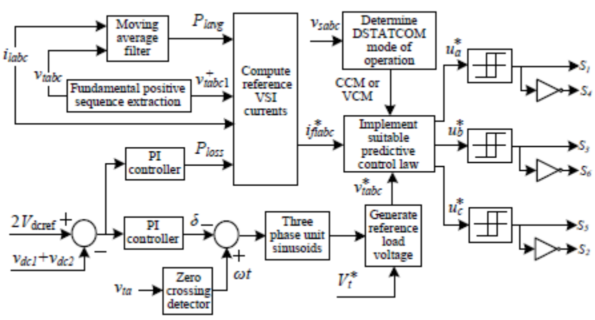


Figure 5. Control block diagram of interactive DSTATCOM [35]

A reduced rating inverter for sag mitigation is required. The voltage sag refers to reduction in load voltage from 0.9 to 0.1 p.u. of nominal value for half cycle to one minute. It means that if V_s is 0.9232 p.u. then PCC will experience sag. Thus, it is possible to set limit for sag occurrence as V_s = 0.9232 p.u. and is denoted as lower limit. A swell is defined as increase in terminal voltage from 1.1 to1.8 p. u. from nominal voltage for half cycle to one minute. V_s = 1.1 p. u. will produce a swell at PCC at worst normal operating condition and is denoted by upper limit. Thus, it can be concluded that-

(1) If V_s is less than 0.9232 p.u. and greater than 1.1 p.u. then the DSTATCOM can operate in VCM to regulate load voltage.

(2) If source voltage lies between 0.9232 to 1.1 p. u. then the DSTATCOM can operate in CCM.

Comparison of performance of interactive DSTATCOM with CCM operation is shown in Table II and with VCM operation is shown in Table III.

Table II. Comparison of Performance of Interactive DSTATCOM with CCM Operation [35]

Performance index	CCM operation	Interactive DSTATCOM
Normal operation	Inverter supplies reactive and harmonic component of load current	Inverter supplies reactive and harmonic component of load current
Voltage disturbances	No voltage regulation capability, taken out from service	Maintains a constant voltage at the load terminal
Load operation	Does not guarantee continuous load Operation	Guarantees Continuous Load Operation
Utilization	Only for load compensation	Maximized utilization, A Single Compensator Provides Several operational features

Table III. Comparison of Performance of Interactive DSTATCOM with VCM Operation [35]

Performance index	VCM operation	Interactive DSTATCOM
Normal operation	Inverter exchanges reactive power with the source	No reactive power exchange with the source. Hence, reduced current is supplied by the inverter
Voltage disturbances	Maintains constant voltage of 1.0 pu at load terminal	Maintains a constant voltage at 0.9 pu at load terminal which is sufficient for load operation
Power rating	More current is required for voltage compensation and therefore power rating of VSI needed is more	With reduced current Requirement for sag mitigation, reduced power rating VSI needed
Loss and efficiency	More current injection means more losses in inverter and feeder. Also, the efficiency reduces	Reduced losses and Efficiency is Improved

B) DSTATCOM in Smart Grids

Power quality in smart grids can be improved by DSTATCOM which compensates the voltage sags, unbalanced voltages and voltage harmonics caused by unbalanced loads and nonlinear loads [61].The compensation of the voltage sags is carried out by injecting reactive power, while the voltage harmonics and voltage imbalances are reduced by canceling out the harmonics and the imbalances of the grid current. The control scheme is designed in the synchronous reference frame with a nested control structure which contains PI controllers and resonant regulators. These regulators are tuned at the harmonic frequencies to be eliminated and can be implemented to incorporate an update of those frequencies. Fig. 6 shows equivalent circuit of a DSTATCOM connected to the grid at the point of common coupling.

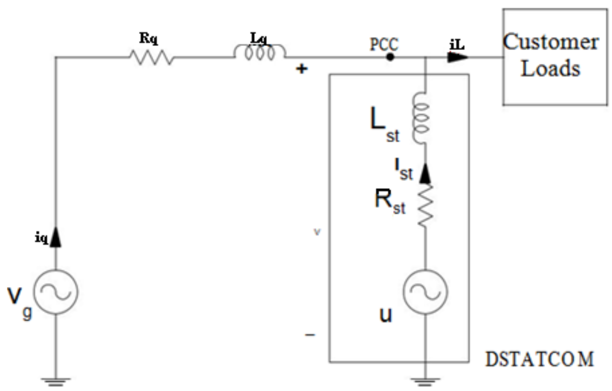


Figure 6. Single-phase equivalent circuit of a DSTATCOM connected to the grid [61]

Fig. 7. shows the control system of the DSTATCOM current for both axes (i.e., the inner control loops), where P(s) is a transfer function derived from the model (1), and $R_1(s)$ and k_{pi} are an integral regulator and a proportional constant with which to control the DC values of the DSTATCOM current for the d and q axes (i.e., the positive sequence of the fundamental harmonic in the three-phase system) [61].

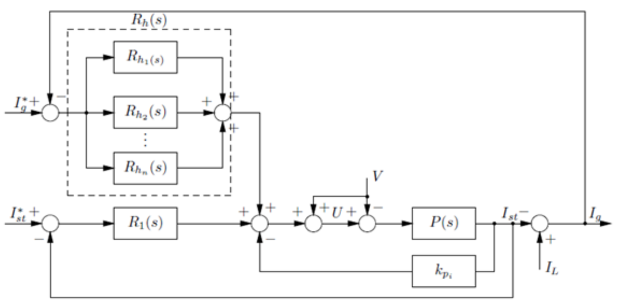


Figure 7. Configuration of the current control system for d and q axes without distinction [61]

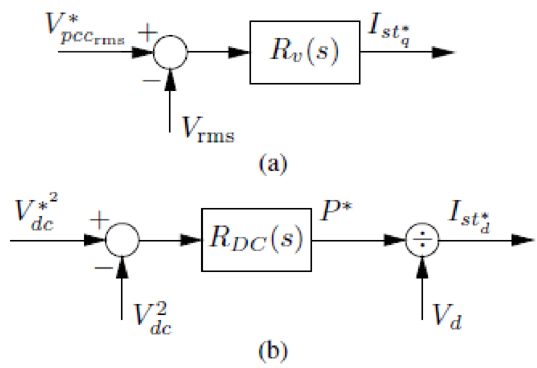


Figure 8. Control schemes for (a) RMS voltage at the PCC (b)Voltage of the DC capacitor [61]

Fig. 8. shows the outer control loops used to control the voltage at the PCC, and to maintain the voltage of the DC capacitor constant, respectively. These outer control chains are designed to be slower than the inner control loop. Thus allowing a decoupled design of the different control systems. The controller of the PCC voltage $R_v(s)$ generates the reference of the q-axis current $I_{stq}(s)$ from the comparison of the reference RMS value of the PCC voltage $V_{pccrms}(s)$ and the RMS measure of the voltage at the PCC $V_{rms}(s)$. The regulator $R_{DC}(s)$ generates the active power reference P*(s) by using the difference between the variables V_{dc} (s) and $V_{dc}{}^2(s)$. The reference for the d-axis current $I_{std}(s)$ is obtained by dividing the active power reference by the d component voltage at the PCC $V_d(s)$. Both regulators $R_v(s)$ and $R_{DC}(s)$ are PI controllers which are designed using the pole placement technique with the following transfer functions:

$$\frac{d}{dt}\begin{bmatrix} i_{st_d} \\ i_{st_q} \end{bmatrix} = \begin{bmatrix} -\frac{R_{st}}{L_{st}} & \omega_1 \\ -\omega_1 & -\frac{R_{st}}{L_{st}} \end{bmatrix}\begin{bmatrix} i_{st_d} \\ i_{st_q} \end{bmatrix} + \frac{1}{L_{st}}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} u_d - v_d \\ u_q \end{bmatrix} \quad (1)$$

$$p = v_d i_{st_d} + v_q i_{st_q} = v_d i_{st_d} \quad (2)$$

The current reference $I_{st}(s)$ is provided by the control systems depicted in Fig. 8(a). A feedforward term of the PCC voltage V(s) is added to improve the transient response of the closed-loop system. In order to cancel out imbalances and harmonics in the grid current, the control system also includes various resonant regulators with a generic transfer function:

$$q = -v_d i_{st_q} + v_q i_{st_d} = -v_d i_{st_q} \quad (3)$$

where $C_a(s)$ is a phase-lead compensator, and the parameter ω_{hn} of $C_b(s)$ is the angular frequency of the harmonic to be eliminated. The regulator $R_{hn}(s)$ has a band pass structure. This minimizes, up to certain limits, the interaction between regulators that can be added in parallel, and simplifies the control design, which can easily be carried out by using frequency response techniques. As the goal is to eliminate the imbalances and harmonics of the grid current, the reference $I_g(s)$ must be zero. The overall resonant regulator $R_h(s)$ is therefore calculated as:

$$p_{C_{DC}} = -\frac{1}{2}C\frac{d\left(v_c\right)^2}{dt} \quad (4)$$

It should be noted that, if $X_o(s)$ and $X_i(s)$ were the output and input, respectively, of the transfer function $C_b(s)$ in Eq.(3), then it would be possible to write:

$$R_v(s) = \frac{k_v}{s} \tag{5}$$

From an implementation point of view, if an estimation method of the grid frequency ω_1 is used, and taking into account that $\omega_{hn} = hn\omega_1$, Eq. (5) is more useful as regards implementing an adaptive version of the resonant controller than that defined in Eq. (3). It should be noted that the addition of the resonant controllers allows, up to certain limits, the DSTATCOM to operate in the overmodulation region, i.e., the voltage of the DC voltage can be decreased, as they remove the low-frequency harmonics caused by the overmodulation process.

C) Voltage control in L.V Networks (voltage control)

Voltage rise is the main issue which limits the capacity of Low Voltage (LV) network to accommodate more Renewable Energy (RE) sources. In addition, voltage drop at peak load period is a significant power quality concern. If DSTATCOM works in localized control mode it is difficult to guarantee an acceptable and efficient operating point under various factors. On the other hand, the centralized control mode is neither practical nor reliable, since it requires global network information. Therefore, a more practical control strategy can be provided through a distributed control mode by using more than one DSTATCOM as proposed in [62].

A new robust voltage support strategy is proposed [62]. It is based on distributed co-ordination of multiple DSTATCOM's. The study focuses on LV networks with Photo -Voltaic (PV) as the Renewable energy (RE) source for customers. It is found that less reactive power is required for a particular voltage support as compared with other voltage support strategies.

Let us consider a network that has *n* distributed DSTATCOMs. The proposed distributed control structure for this network is shown in Fig. 9 (a) in which the dashed arrows show the information flow. In this structure, the neighbouring DSTATCOMs, which have the most effect on voltage of each other, are communicated to coordinate their operation. The internal control structure of each DSTATCOM is shown in Fig. 9 (b). To find the network operation mode, four voltage limits are defined. To avoid overvoltage, $V_{max\_desirable}$ and $V_{max\_critical}$ determine the network operation mode. If all DSTATCOM bus voltages are less than $V_{max\_critical}$, network is in normal operation mode and coordination between them is not needed. However, if the bus voltage of any DSTATCOM violates the limit, it initiates the distributed algorithm, as will be explained later, to support the voltage. The coordination will continue until all voltages are reduced to less than $V_{max\_desirable}$. In this situation, all DSTATCOMs decrease their reactive power, step by step until stop operating. The same procedure is applied to avoid undervoltage in which $V_{min\_desirable}$ and $V_{min\_critical}$ determine the network operation mode [62].

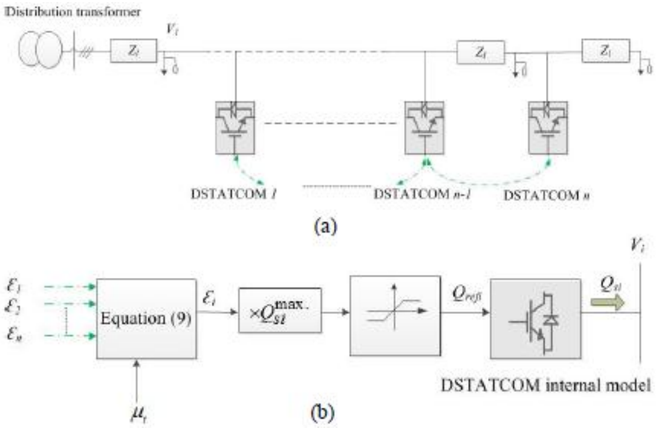


Figure 9. Proposed approach (a) Distributed control structure (b) Internal control for each DSTATCOM [62]

3. LOAD BALANCING

A) Power quality Improvement in Isolated Distributed generating system using DSTATCOM

The control of a synchronous reluctance generator (SYRG) driven by a biogas biomass diesel engine as a prime mover in a distributed Power Generating system is reported in [63].

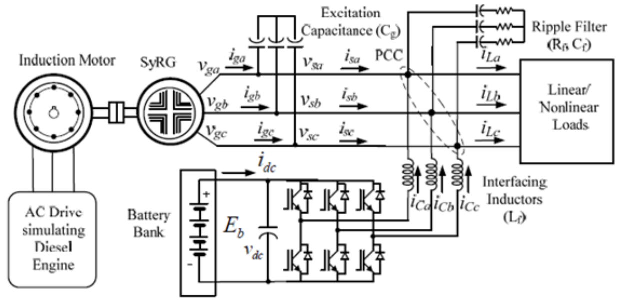


Figure10. Schematic diagram of Synchronous Reluctance Generator system with DSTATCOM [63]

Fig.10. shows schematic diagram of Synchronous Reluctance Generator system with DSTATCOM. The synchronous reluctance generator (SYRG) is used as a source to feed linear and nonlinear loads. An adaptive neural network-based control algorithm for DSTATCOM is used for harmonics suppression, load balancing and voltage regulation in three-phase SYRG system with a battery energy storage system. This Adaptive neural network control algorithm is used for extraction of active and reactive power components of distorted load currents. These components of load currents are used for estimation of reference source currents to generate the gating pulses of VSC used as DSTATCOM. The performance of DSTATCOM is observed satisfactory for this type of generating system under balanced and unbalanced loads.

4. REACTIVE POWER COMPENSATION

A) Single phase operation of microgrid

Various researchers have proposed a co- ordinated control of distributed generators (DGs) and DSTATCOM in a microgrid [64-81]. The power flow and voltage at different locations of the feeders are communicated to the DSTATCOM to modulate the reactive compensation. The single phase DSTATCOM compensates for the reactive power deficiency in phase while the DGs supply maximum available active power. The maximum available active power is fixed to a value lower than maximum active power to increase reactive power injection capability of the DGs. It is shown that the proposed method can always ensure acceptable voltage regulation [64].

Fig. 11 shows the system under consideration with three feeders' sections where DGs and loads are connected. The loads and DGs are suffixed with the phase on which it is connected with (as DG_{1a}), to represent the first DG connected to phase a. It is assumed that the DGs are Voltage Source Converter (VSC) interfaced. In grid connected mode, the DGs supply the maximum power available while the utility supplies any additional power required by the loads. During islanded operation, the total power demand is supplied by the DGs. It is assumed that if the power demand in the islanded mode is more than the total power output of the DGs, loads are partly shed to meet the power balance. Loads are represented by L_{d1a}, L_{db1} etc. The locations of the single-phase compensating devices (DSTATCOM) are indicated as DSTATa, DSTATb and DSTATc. Feeder impedance is also considered.

DSTATCOM can provide the required voltage support and power quality improvement. In [75], a DSTATCOM is proposed to alleviate variation of both positive-sequence and negative-sequence voltages at the fundamental frequency Moreover, a DSTATCOM can provide microgrid a ride through capability during transients [76]. But the active power and reactive power in a low voltage network are strongly coupled and regulation in voltage should consider both the real and reactive power flow [77].

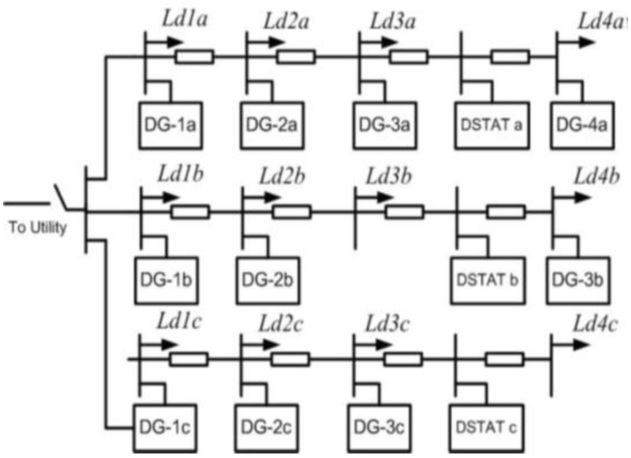


Figure 11. Microgrid System under consideration

An excellent study for compensation of reactive power and unbalance caused by various loads in distribution system is presented in [78]. It covers the instantaneous reactive power method with a synchronous reference frame method. Power quality improvement in a four-wire electric distribution system is shown in [79]. A Current-Controlled Voltage Source Inverter (CC-VSI) with a DC bus capacitor is used as a DSTATCOM. The DSTATCOM improves the supply power factor, eliminates harmonics, provides load balancing and improves the load terminal voltage at the Point of Common Coupling (PCC). The DC bus voltage of the DSTATCOM and three phase voltages at PCC are used as feedback signals for PI controllers. The operation of DSTATCOM can be done by either voltage control or in current control mode [80]. In the voltage control mode, the DSTATCOM can force the voltage of a distribution bus to be balanced sinusoids. In the current control mode, it can cancel distortion caused by the load. In a microgrid, the DGs operate with voltage control and to achieve reactive power coordination with the DGs, it is desirable to control the DSTATCOM in voltage control. In single phase operation, where the feeders are geographically far apart, it is not always possible to achieve reactive compensation by three phase devices at proper location. A coordinated control of the DGs and DSTATCOM needs exchange of information and require a communication infrastructure. Communication setup is increasingly being deployed to meet utility needs for distributed energy resources [81]. Using communication, it would be possible to improve the voltage support with DSTATCOM and DGs. During high loading period, the DGs reach their reactive power limits and the voltage falls below the acceptable regulation limit. With a frequent load change and continuous change in power generation of the DGs, it is important that the reactive compensation act promptly with change in voltage. As the power flow in the line has impact on the voltage, it would be beneficial to modulate the reactive compensation based on the power flow in the line. The main contribution of the paper lies in improving reactive compensation with coordinated control of DGs and DSTATCOM with communication in loop for a microgrid. The proposed control ensures stable fast acting reactive power compensation within voltage regulation limit based on power flow. Converter control with integrated communication network demonstrates stable operation while data traffic analysis shows the communication network requirements and limitations for this purpose. Many other researchers have worked in the areas of microgrid and converter interfaced micro sources [82-98]. Reactive compensation in distribution network is also studied by various researchers [99-105].

FUTURE TRENDS

The DSTATCOM can practically solve voltage and current related power quality problems such as harmonic elimination, load balancing, voltage regulation, power factor correction and neutral current compensation in distribution system. However, the high cost of DSTATCOM is the main obstacle for its wide implementation especially for developing countries trying to improve power quality of power system. Hence in future extensive research work needs to be undertaken by researchers to reduce the cost of DSTATCOM without affecting the performance efficiency. Also use of neural networks in control techniques of DSTATCOM is likely to be widely used in the future. Renewable energy (RE) penetration into the electric utility grid is increasing day by day and intermittent nature of these resources affects the quality of supplied power. The weather conditions such as wind speed variations and variable solar insolation affect the power output of RE sources. Implementation of DSTATCOM in RE based power system are required to be explored more. In future an important area of research would be the deployment of DSTATCOM in charging stations for hybrid and electric vehicles.

CONCLUSION

A comprehensive literature review of applications of DSTATCOM in distribution system is presented in this paper. The power flow between the DSTATCOM and PCC is controlled by controlling the phase angle between the inverter output voltage and voltage at PCC. Typical applications of DSTATCOM include mitigation of many PQ problems like harmonic pollution power factor correction, load balancing, noise cancellation, sag, swells, impulses, unbalances and fluctuations in voltage. It can be concluded from this paper that DSTATCOM is a versatile equipment for power quality improvement in distribution system. The future trends in applications of DSTATCOM are also indicated.

REFERENCES

[1] Mustapha Benghanem, AzeddineDraou, ‘A new modelling and control analysis of an advanced static VAR compensayor using a three - level (NPC) inverter topology’, Journal of Electrical Engineering, Vol. 57, No. 5, 285-290, 2006.

[2] L. Xu, V.G. Agelidis and E. Acha, ‘Development considerations of DSP controlled PWM VSC-based STATCOM’, IEE ProcElectr. Power Appl., Vol. 148, No. 5, September 2001.

[3] Ranjan Kumar Mallick and Satyantan Sinha, “Improvement of power quality in DFIG based wind farm using optimized DSTATCOM”, IEEE 2015.

[4] Suman Nath, Somnath Rana , “ The modelling and simulation of wind energy based power system using MATLAB”, ISSN journal: 2231-4407, Volume-1, Issue-2, 2011.

[5] Prof Alexander Emnuael, “Analysis and Mitigation of Harmonics in Wind Turbine Transformers”, A Major Qualifying Project by Stephen Cialdea, Marcus Peart, and Warranyu Walton, 2012.

[6] Reigh Walling, Dave Muller, “Harmonic and resonant issues in wind power”, IEEE PES general meeting, July 26th, Detroit, MI, 2012 .

[7] Marcelo G. Molina, Pedro E. Mercado, “Power Flow Control Of Microgrid with Wind Generation Using a Dstatcom-Uces”, CONICET, Instituto de Energia Electrica, Universidad de San Juan, San Juan, Argentina, 2010.

[8] Pinaki Mitra, Ganesh Kumar Venayagamoorthy, “An Adaptive Control Strategy For DSTATCOM Applications In an Electric Ship Power System”, IEEE Transaction for Power Electronics, VOL. 25, NO. 1, January 2010.

[9] A. Rohani, M. Joorabian, “Modelling And Control Of Dstatcom Using Adaptive Hysteresis Band Controller In Three Phase Four Wire Distributions System”, 5TH Power Electronics, Drive Systems and Technologies Conference (PEDSTC 2014), Tehran, Iran, Feb 5-6, 2014.

[10] S.Srivastava, Astha Manaktala, Kamayani Sadhwani, M.Gupta, “On Comparing The Performance Of Genetic Algorithm Optimised PI And Fractional Order Pi Controller For Power Quality Enhancement”, International Conference on Power and Energy Systems, 2011.

[11] Pinaki Mitra, Ganesh K. Vengayamoorthy, “A Dstatcom Controller Tuned By Particle Swarm Optimization For An Electric Ship Power System”, IEEE Power and Energy Society General Meeting, 2008.

[12] Nagesh Geddada, Srinivas Bhaskar Karanki, Mahesh K. Mishra, “Synchronous Reference Frame Based Current Controller With Spwm Switching Strategy For Dstatcom Applications”, IEEE International Conference On Power Electronics, Drives and Energy System, Bengaluru, India, December 16-19, 2012.

[13] M. A. Eldery, E. F. El-Saadany and M. M. A. Salama, “Sliding Mode Controller For Pulse Width Modulation Based DSTATCOM”, Canadian Conference on Electrical and Computer Engineering, 2006.

[14] Kiran Kumar Pinapatruni, Krishna Mohan L., “DQ Based Control Of Dstatcom For Power Quality Improvement”, Vsrd-Ijeece, Vol. 2(5), pp. 207-227, 2012.

[15] Gokulnanda Sahu and Kamalakanta Mahapatra, “Model predictive control of DSTATCOM for power quality improvement: Modelling, simulation and analysis-Part1”, IEEE Power, Communication and Information Technology Conference (PCITC), 2015.

[16] Rosa, Francisco C. De La, “Harmonics and Power Systems,” New York, Taylor & Francis Group, LLC, 2006.

[17] H. Akagi, E. H. Watanabe, and M. Aredes, “Instantaneous Power Theory and Applications to Power Conditioning”, Hoboken, NJ: Wiley, 2007.

[18] A Moreno-Munoz, "Power Quality: Mitigation Technologies in a Distributed Environment", London, U. K.: Springer-Verlag, 2007.

[19] G. Sahu, K. Mahapatra, "Real time implementation of digital filter on control strategy of DSTATCOM for load compensation under distorted utility condition.", in Proc. IEEE Conf. Prime Asia, pp.164-169, 2013.

[20] Gokulananda Sahu, Kamalakanta Mahapatra", A novel control strategy of DSTATCOM for load compensation under distorted utility condition", in Proc.IEEE conf. ICAEE, pp.1-6, 2014.

[21] M. P. Kazmierkowski, R. Krishnan, and F. Blaabjerg, Control in Power Electronics, New York: Academic, 2002.

[22] N. Mohan, T. M. Undeland, and W. P. Robbins, Power Electronics, 2nd ed. Hoboken, NJ: Wiley, 1995.

[23] Linder and R. Kennel, "Model predictive control for electrical drives,"in Proc. IEEE PESC, Recife, Brazil, pp. 1793–1799, 2005.

[24] P. Cortés, J. Rodríguez, D. E. Quevedo, and C. Silva, "Predictive current control strategy with imposed load current spectrum," IEEE Trans. Power Electron., vol. 23, no. 2, pp. 612–618, Mar. 2008.

[25] P. Antoniewicz and M. P. Kazmierkowski, "Predictive direct power control of three-phase boost rectifier," Bull. Pol. Acad. Sci., vol. 54, no.3, pp. 287–292, 2006.

[26] J. Rodríguez, J. Pontt, C. Silva, M. Salgado, S. Rees, U. mmann, P. Lezana, R. Huerta, and P. Cortés, "Predictive control of a three-phase inverter," Electron. Lett., vol. 40, no. 9, pp. 561–562, Apr. 29, 2004.

[27] J. Rodriguez, J. Pontt, C. Silva, P. Cortes, U. Amman, and S.Rees,"Predictive current control of a voltage source inverter," in Proc. IEEE35th Annu. PESC, Jun. 2004, vol. 3, pp. 2192–2196.

[28] J. Rodríguez, J. Pontt, C. Silva, P. Correa, P. Lezana, P. Cortés, and U. Ammann, "Predictive current control of a voltage source inverter," IEEE Trans. Ind. Electron., vol. 54, no. 1, pp. 495–503, Feb. 2007.

[29] J. Rodríguez, J. Pontt, C. Silva, P. Cortés, S. Rees, and U. Ammann, "Predictive direct torque control of an induction machine," in Proc. 11th Int. EPE-PEMC, Riga, Latvia, Sep. 2–4, 2004.

[30] R. Vargas, P. Cortes, U. Ammann, J. Rodriguez, and J. Pontt, "Predictive control of a three-phase neutral-point-clamped inverter," IEEE Trans. Ind.Electron., vol. 54, no. 5, pp. 2697–2705, Oct. 2007.

[31] S. Muller, U. Ammann, and S. Rees, "New time-discrete modulation scheme for matrix converters," IEEE Trans. Ind. Electron., vol. 52, no. 6,pp. 1607–1615, Dec. 2005.

[32] E. I. Silva, B. P. McGrath, D. E. Quevedo, and G. C. Goodwin, "Predictive control of a flying capacitor converter," in Proc. Amer. Control Conf.,New York, pp. 3763–3768, Jul. 2007.

[33] Saetieo, S., Devaraj, R., and Torrey, D. A., "The design and implementation of a three phase active power filter based on sliding mode control," IEEE Trans. Ind. Appl., Vol. 31, No. 5,pp. 993–1000, September 1995.

[34] IEEE Recommended Practices and Requirements /or Harmonic Control in Electrical Power Systems, IEEE Standard 519, 1992.

[35] Chandan Kumar and Mahesh Mishra, "Operation and control of an improved performance interactive DSTATCOM", IEEE Transactions on Industrial Electronics, 2015.

[36] M. Bollen, "Understanding power quality problems", IEEE press New York, ch. 1, pp. 1-35, 2000.

[37] A. Ghosh and G. F. Ledwich, "Power quality enhancement using custom power devices", Kluwer Publications, 2002.

[38] H. Akagi and K. Isozaki, "A hybrid active filter for a three-phase 12-pulse diode rectifier used as the front end of a medium-voltage motor drive," IEEE Trans. Power. Electron., vol. 27, no. 1, pp. 69–77, Jan. 2012.

[39] B. Singh and S. Arya, "Back-propagation control algorithm for power quality improvement using DSTATCOM," IEEE Trans. Ind. Electron., vol. 61, no. 3, pp. 1204–1212, Mar. 2014.

[40] K. Karanki, G. Geddada, Mahesh K. Mishra, and B. Kumar, "A modified three-phase four-wire UPQC topology with reduced DC-link voltage rating," IEEE Trans. Ind. Electron., vol. 60, no. 9, pp. 3555–3566, Sep. 2013.

[41] A. Bhattacharya, C. Chakraborty, and S. Bhattacharya, "Parallel-connected shunt hybrid active power filters operating at different switch-ing frequencies for improved performance," IEEE Trans. Ind. Electron, vol. 59, no. 11, pp. 4007–4019, Nov. 2012.

[42] S. Rahmani, A. Hamadi, K. Al-Haddad, and L. Dessaint, "A combination of shunt hybrid power filter and thyristor-controlled reactor for power quality," IEEE Trans. Ind. Electron., vol. 61, no. 5, pp. 2152–2164, May 2014.

[43] A. Bhattacharya and C. Chakraborty, "A shunt active power filter with enhanced performance using ANN-based predictive and adaptive controllers," IEEE Trans. Ind. Electron., vol. 58, no. 2, pp. 421–428, Feb. 2011.

[44] B. Singh, C. Jain, and S. Goel, "Ilst control algorithm of single-stage dual purpose grid connected solar pv system," IEEE Trans. Power Electron., vol. 29, no. 10, pp. 5347–5357, Oct. 2014.

[45] H. Fujita and H. Akagi, "Voltage-regulation performance of a shunt active filter intended for installation on a power distribution system," IEEE Trans. Power. Electron., vol. 22, no. 3, pp. 1046–1053, May 2007.

[46] Mahesh K. Mishra, A. Ghosh, and A. Joshi, "Operation of a DSTAT-COM in voltage control mode," IEEE Trans. Power Del., vol. 18, no. 1,258–264, Jan. 2003.

[47] A. Jain, K. Joshi, A. Behal, and N. Mohan, "Voltage regulation with STATCOMs: modeling, control and results," IEEE Trans. Power. Del., vol. 21, no. 2, pp. 726–735, Apr. 2006.

[48] G. Ledwich and A. Ghosh, "A flexible DSTATCOM operating in voltage or current control mode," Generation, Transmission and Distribution, IEE Proceedings-, vol. 149, no. 2, pp. 215–224, Mar. 2002.

[49] C. Kumar and Mahesh K. Mishra, "A voltage-controlled DSTATCOM for power-quality improvement," IEEE Trans. Power Del., vol. 29, no. 3, 1499–1507, Jun. 2014.

[50] M. Rivera, V. Yaramasu, A. Llor, J. Rodriguez, B. Wu, and M. Fadel, "Digital predictive current control of a three-phase four-leg inverter," IEEE Trans. Ind. Electron., vol. 60, no. 11, pp. 4903–4912, Nov. 2013.

[51] P. Cortes, J. Rodriguez, C. Silva, and A. Flores, "Delay compensation in model predictive current control of a three-phase inverter," IEEE Trans. Ind. Electron., vol. 59, no. 2, pp. 1323–1325, Feb. 2012.

[52] S. Srikanthan and Mahesh K. Mishra, "DC capacitor voltage equaliza-tion in neutral clamped inverters for DSTATCOM application," IEEE Trans. Ind. Electron., vol. 57, no. 8, pp. 2768–2775, Aug. 2010.

[53] O. Kukrer, "Discrete-time current control of voltage-fed three-phase PWM inverters," IEEE Trans. Power Electron., vol. 11, no. 2, pp. 260– 269, Mar. 1996.

[54] R. Vargas, P. Cortes, U. Ammann, J. Rodriguez, and J. Pontt, "Predictive control of a three-phase neutral-point-clamped inverter," IEEE Trans. Ind. Electron., vol. 54, no. 5, pp. 2697–2705, Oct. 2007.

[55] P. Cortes, J. Rodriguez, D. Quevedo, and C. Silva, "Predictive current control strategy with imposed load current spectrum," IEEE Trans. Power. Electron., vol. 23, no. 2, pp. 612–618, Mar. 2008.

[56] L. Malesani, P. Mattavelli, and S. Buso, "Robust dead-beat current control for pwm rectifiers and active filters," IEEE Trans. Ind. Appl., vol. 35, no. 3, pp. 613–620, May 1999.

[57] K. Ogata, "Discrete-time control systems", Prentice Hall Englewood Cliffs, NJ, vol. 2., 1995.

[58] W. Ghzaiel, M.-B. Ghorbal, I. Slama-Belkhodja, and J. Guerrero, "A novel grid impedance estimation technique based on adaptive virtual resistance control loop applied to distributed generation inverters," in15th European Conference on Power Electronics and Applications (EPE), 2013, pp. 1–10, Sep. 2013.

[59] N. Hoffmann and F. Fuchs, "Minimal Invasive Equivalent Grid Impedance Estimation in Inductive–Resistive Power Networks Using Extended Kalman Filter", IEEE Transactions on Power Electronics, Vol. 29, Issue: 2, Feb. 2014.

[60] A. Ghosh and G.F. Ledwich, "Power quality enhancement using custom power devices", Kluwer Publications, 2002.

[61] Pedro Roncero-Sanchez, "Harmonic and imbalance voltage mitigation in smart grids: A DSTATCOM based solution", European Union, 2015.

[62] G. Mokhtari et al, "A new distributed control strategy to coordinate multiple DSTATCOMS in L.V network", 4th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2014.

[63] Sabha Raj Arya et al, "Power quality improvement in isolated distributed generating system using DSTATCOM", IEEE-IACC, 2014.

[64] Ritwik Mujumdar, "Reactive power compensation in single phase operation of microgrid", IEEE Transactions, 2011.

[65] X. Yoasuo, C. Liuchen, B. K. Soren, B. Josep and S. Toshihisa,"Topologies of single-phase inverters for small distributed power generators: an overview", IEEE Trans. on Power Electronics, vol. 19, pp. 1305-1314, Sep 2004.

[66] T. E. McDermott, R. C. Dugan, "Distributed generation impact on reliability and power quality indices" Rural Electric Power Conference, 2002.

[67] Provides Power Quality for 21st Century Needs, National Energy Technology Laboratory, US Department of Energy, January, 2007.

[68] R. Strezelecki and G. Benysek, "Active Power Quality Controllers", Power Electronic in Smart Electrical Energy Network, Springer, 2011.

[69] R. Majumder, A. Ghosh, G. Ledwich, F. Zare, "Operation and control of single phase micro-sources in a utility connected grid," IEEE Power & Energy Society General Meeting, 2009. PES'09, pp.1-7, 26-30 July 2009.

[70] F. Shahnia, R. Majumder, A. Ghosh, G. Ledwich and F. Zare, "Sensitivity analysis of voltage imbalance in distribution networks with rooftop PVs," Power and

Energy Society General Meeting, vol., no., pp.1-8, 25-29 July 2010.

[71] Z. Tao; B. Francois, "Energy Management and Power Control of a Hybrid Active Wind Generator for Distributed Power Generation and Grid Integration", IEEE Transactions on Industrial Electronics, vol.58, no.1, pp.95-104, Jan. 2011.

[72] Z. Qing-Chang ,G. Weiss, G., "Synchronverters: Inverters That Mimic Synchronous Generators," IEEE Transactions on Industrial Electronics, vol.58, no.4, pp.1259-1267, April 2011.

[73] Y. Shuitao, L. Qin, F. Z. Peng, Q. Zhaoming, "A Robust Control Scheme for Grid-Connected Voltage-Source Inverters," IEEE Transactions on Industrial Electronics, vol.58, no.1, pp.202-212, Jan.2011.

[74] I. J. Balaguer, L. Qin Lei, Y. Shuitao, U. Supatti, P. Fang Zheng, "Control for Grid-Connected and Intentional Islanding Operations of Distributed Power Generation," IEEE Transactions on Industrial Electronics, vol.58, no.1, pp.147-157, Jan. 2011.

[75] J. M. Guerrero, J. Matas, L.G. de Vicuna, M. Castilla, J. Miret, "Decentralized Control for Parallel Operation of Distributed Generation Inverters Using Resistive Output Impedance," IEEE Transactions on Industrial Electronics, vol.54, no.2, pp.994-1004, April 2007.

[76] J.M.Guerrero, J.C.Vasquez, J. Matas, M.Castilla, L.G. de Vicuna, "Control Strategy for Flexible Microgrid Based on Parallel Line-Interactive UPS Systems," IEEE Transactions on Industrial Electronics, vol.56, no.3, pp.726-736, March 2009.

[77] A. Vaccaro, G. Velotto, A.F. Zobaa, "A Decentralized and Cooperative Architecture for Optimal Voltage Regulation in Smart Grids," IEEE Transactions on Industrial Electronics, vol.58, no.10, pp.4593-4602, Oct. 2011.

[78] T. Sauter, M. Lobashov, "End-to-End Communication Architecture for Smart Grids," IEEE Transactions on Industrial Electronics, vol.58, no.4, pp.1218-1228, April 2011.

[79] P. Rodríguez, A. Luna, I. Candela, R. Mujal, R. Teodorescu, F. Blaabjerg, "Multiresonant Frequency-Locked Loop for Grid Synchronization of Power Converters Under Distorted Grid Conditions," IEEE Transactions on Industrial Electronics, vol.58, no.1, pp.127-138, Jan. 2011.

[80] Clean Energy Council Australia, http://www.cleanenergycouncil.org.au/cec/home.html.

[81] 'IEEE Application Guide for IEEE Std 1547, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems,' IEEE Std 1547.2-2008 , vol., no., pp.1-207, April 15 2009.

[82] L. Tzung-Lin, H. Shang-Hung,C.Yu-Hung, "Design of D-STATCOM for voltage regulation in Microgrids," Energy Conversion Congress and Exposition (ECCE), 2010 IEEE, pp.3456-3463, 12-16 Sept. 2010.

[83] R. Majumder, A. Ghosh, G. Ledwich, and F. Zare, "Enhancing the Stability of an Autonomous Microgrid Using DSTATCOM," International Journal of Emerging Electric Power Systems: Vol. 10: Issue 5, Article 5, 2009.

[84] R. Majumder, G. Ledwich, A. Ghosh, S. Chakrabarti and F. Zare, "Droop Control of Converter-Interfaced Microsources in Rural Distributed Generation," IEEE Transactions on Power Delivery, vol.25, no.4, pp.2768-2778, Oct. 2010.

[85] B. Singh, J. Solanki, "A Comparison of Control Algorithms for DSTATCOM," IEEE Transactions on Industrial Electronics, vol.56, no.7, pp.2738-2745, July 2009.

[86] B.Singh, A. Adya, A.P. Mittal, J.R.P. Gupta, "DSTATCOM for power quality improvement in a four-wire electric distribution system", International Journal of Global Energy Issues (IJGEI), Vol. 26, No. 3/4, 2006.

[87] G. Ledwich, A. Ghosh, "A flexible DSTATCOM operating in voltage or current control mode," IEE Proceedings Generation, Transmission and distribution, vol.149, no.2, pp.215-224, Mar 2002.

[88] Integrated Communications- A System View of Modern Grid, National Energy Technology Laboratory, US Department of Energy, Office of Energy Delivery and Energy Reliability, February, 2007.

[89] R. Majumder, "Modeling, stability analysis and control of microgrid", PhD thesis, Queensland University of Technology, 2010.

[90] Qualnet, Scalable Network, www.scalable-networks.com.

[91] L. Tzung-Lin, H. Shang-Hung, C.Yu-Hung, "Design of D-STATCOM for voltage regulation in Microgrids," Energy Conversion Congress and Exposition (ECCE), 2010 IEEE, pp.3456-3463, 12-16 Sept. 2010.

[92] R. Majumder, A. Ghosh, G. Ledwich, and F. Zare, "Enhancing the Stability of an Autonomous Microgrid Using DSTATCOM," International Journal of Emerging Electric Power Systems: Vol. 10: Issue 5, Article 5, 2009.

[93] R. Majumder, G. Ledwich, A. Ghosh, S. Chakrabarti and F. Zare, "Droop Control of Converter-Interfaced Microsources in Rural Distributed Generation," IEEE Transactions on Power Delivery, vol.25, no.4, pp.2768-2778, Oct. 2010.

[94] Integrated Communications- A System View of Modern Grid, National Energy Technology Laboratory, US Department of Energy, Office of Energy Delivery and Energy Reliability, February, 2007.

[95] E. Rambabu, E.Praveena, P.V.Kishore, "Mitigation of harmonics in distribution system using D-STATCOM," International Journal of Scientific and Engineering Research Volume 2, Issue 11, November-2011.

[96] S. Pushpavalli, A. Cordelia Sumathy, "Harmonic reduction of arc furnaces using DSTATCOM", IOSR Journal of Engineering (IOSRJEN), Vol. 3, Issue 4, pp. 07-14, April 2013.

[97] Randeep Singh Chib, Mehak Sharma, Hartaj Singh, "Active filter and reactive compensation using DSTATCOM", Journal of Engineering Research and studies, IV/IV, Oct-Dec, 2013.

[98] CIGRE, "Static Synchronous Compensator", September 1998.

[99] H.F. Wang, "Applications of damping torque analysis to Statcom control", Electrical power and energy system , Vol.22, pp. 197-204, 2000.

[100] Pierre Giroux, Gilbert Sybille, Hoang Le-Huy, "Modeling and Simulation of a Distribution STATCOM using Simulink's Power System Blockset", IECON'01, the 27th Annual Conference of the IEEE Industrial Electronics Society, 2001.

[101] Narain G. Hingorani, Laszlo Gyugyi, "Understanding FACTS", IEEE press, 2000.

[102] Yong Hua Song, Allan T. Johns, " Flexible AC transmission systems FACTS", IEE Power and energy Series 30, 1999.

[103] Zhiping Yang, " Integration of battery energy storage with Flexible AC transmission system devices", Ph.D Thesis, University of Missouri-Rolla, 2000.

[104] Amir H. Norouzi, "Flexible AC Transmission Systems: Theory , Control and Simulation of the STATCOM and SSSC", MSc Thesis, University of New Brunswick, March 2003.

[105] Ekanayake, J. B., Jenkins, N., "A three-level advanced static var compensator", IEEE Trans. on Power Delivery, Vol. 11, no.1, pp.540-545, 1996.