Comparative power quality analysis of Conventional and Proposed enhanced SRF SOGI-FLL control based DSTATCOM

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ABSTRACT

This paper expresses about comparative power quality analysis in between conventional and proposed control techniques of DSTATCOM under different loading conditions. The goal of DSTATCOM is to reduce power quality problems, that occur due to an unbalanced load, non-linear load, power electronics based load and polluted grid. The performances of DSTATCOM are different in the different control techniques. Three conventional and one proposed control techniques have been employed in the DSTATCOM. Synchronous reference frame (SRF), Sliding mode control (SMC) and ADALINE based LMS control are the conventional techniques while enhanced SRF SOGI-FLL is the proposed technique. The control techniques of DSTATCOM have been compared in terms of load balancing, power factor enhancement, DC link voltage regulation and minimization of harmonics. These control techniques extract reference current for the PWM which generates switching pulses for the DSTATCOM. The complete H-bridge DSTATCOM system along with these control techniques have been implemented in MATLAB /Simulink platform and after execution, superior power quality features of proposed control technique has been investigated.

Key words: DSTATCOM; power quality; SRF; SMC; VSC; SOGI.
INTRODUCTION

With the frequent employment of power electronics gadgets, AC distribution systems are suffering various power quality crisis (Srinivas et al., 2011; Singh et al., 2015). Major portion of loads which are used in industrial, commercial, and residential purpose are made up of power electronics based (Kumar et al., 2014). These types of loads are called as non-linear load. Some of the examples of non-linear loads are Fans, pumps, computers, induction motors (Singh et al., 2011; Arya et al., 2016). These loads are also lagging power factor loads. There are two types of power quality problem: voltage quality and current quality (Singh et al., 2015). DSTATCOM is used to mitigate current quality problems in the distribution systems (Zaveri et al., 2012). Different topologies of three phase four wire based DSTATCOM have been proposed in the literature (Patnaik et al., 2013; Singh et al., 2011). Each topology has its own inherent benefits. Multilevel converter presented in the literature (Zaveri et al., 2012) have low loss, reduced size of filter, higher efficiency than conventional two level voltage source converter. Hence, in this paper H-bridge based multilevel converter has been adopted for the DSTATCOM. H-Bridge converters not only decrease the lower order harmonics, but also have a suitable safety during the operation (Patnaik et al., 2013). Process of DSTATCOM is mostly depending on its control performance applied for reference current extraction and DC voltage regulation (Chauhan et al., 2014; Zainuri et al., 2016). In the last few decades, several researchers have emphasized to construct the proficient and vigorous control of DSTATCOM. To provide the control of DSTATCOM, many strategies have been presented in the literature such as SRF Theory (Kumar et al., 2014; Singh et al., 2011), IRP theory (Zaveri et al., 2012), interpretations and modifications of IRP theory (IEEE Std. 519, 2014), PB theory (Singh et al., 2015), SC theory (Singh et al., 2015), Sliding mode control (Sekhar et al., 2016), ADALINE (Qasim et al. 2014; Bhattacharya et al., 2011), SOGI-MCCF (Chittora et
al., 2018). The major drawbacks of PLL in SRF technique are its digital implementation in circuits, large calculation time, less proficient for correcting voltage distortion, voltage frequency deviation, etc. (Golestan et al., 2017). The foremost problem of Sliding mode control (SMC) technique is to design the sliding surface in dynamic system. It has been seen that if surface design is not proper in dynamic circumstance, it will result unsatisfactory performance. Hence in this work, conventional PLL of SRF has been replaced by SOGI-FLL and developed a novel control philosophy of enhanced SRF SOGI-FLL for the DSTATCOM. SOGI-FLL synchronizes the frequency and phase angle of the grid with power inverter in less time (Hao et al., 2017). This paper also compared the power quality performances of enhanced SRF SOGI-FLL with the other techniques used in the literature. The paper has been separated in divisions. First division illustrates the Introduction of the work in which literature survey and novelty of the work has been included. In division 2, circuit configuration of the three phase four wire H-bridge based DSTATCOM system has been presented. In division 3, various conventional control schemes with its mathematical modeling have been elaborated. In segment 4, the discussions about proposed enhance SRF SOGI-FLL control scheme has been mentioned. Part 5 deals with the results in which performances of DSTATCOM under various loading conditions have been discussed. At last, section 6 concludes the paper.

**H-BRIDGE DSTATCOM**

Figure 1 illustrates the circuit arrangement of three H-bridge DSTATCOM attached to the distribution system. The point on the distribution system at which H-bridge DSTATCOM is bonded known as point of common coupling (PCC). $I_{sa}$, $I_{sb}$, and $I_{sc}$ represent current from the three phase AC mains. $I_{La}$, $I_{Lb}$, $I_{Lc}$ represent current from the load side. The parameter $R_s$ and $L_s$ are the resistance and inductance of the AC mains. $I_c$ and $V_c$ denote the injected current and voltage respectively by the DSTATCOM. $V_{dc}$ is the interior voltage of DC connect capacitor.
of voltage source inverter. The Ripple filter represented as $R_f$ and $C_f$ is fixed at PCC and shunted with the load. The 12 no. of IGBT/diode based switches form three H-bridges VSI (Patnaik et al., 2013). Control algorithms have conventional techniques such as SRF, SMC, ADALINE LMS as well as proposed enhance SRF SOGI-FLL technique. The purpose of hysteresis current controller is to afford switching signal for VSI valves.

Figure 1. Test System based on three H-bridge DSTATCOM.
CONTROL PERFORMANCES

To generate the switching signals for the VSI switches of H-bridge DSTATCOM, control performances such as SRF, SMC, ADALINE LMS and proposed enhance SRF SOGI-FLL technique have been adopted. The discussion about the above control performances are below:

SYNCHRONOUS REFERENCE FRAME THEORY

SRF generates the three phase reference source current signal which is compared with the actual three phase source current. PWM generator gives pulses from three phase error source current signal. The input signals for the SRF are three phase PCC voltage, three phase load current (sensed from distribution system) and DC link voltage (sensed from VSI). Firstly, three phase stationary signal is translated into corresponding synchronously rotating d-q-o signal by Clarke transformation, and then low pass filter is employed for extorting ripples. The PCC voltage signals are passed by three-phase PLL in order to generate sine and cosine signals for Clarke transformation and inverse Clarke transformation (Singh et al., 2015). On DC bus, PI controller produces $I_{loss}$ component. On AC bus, PI controller produces $I_{QDSTAT}$ component.
The reference d-q current is given by

\[ I_d^* = I_{dDC} + I_{loss} \]
\[ I_q^* = I_{qDC} + I_{QDSTAT} \] (1)

The Inverse Clarke transformation converts reference (d-q-0) current into reference (a-b-c) current. The detail discussion on synchronous reference frame has been depicted in Figure 2.

**SLIDING MODE CONTROL**

Sliding mode controller provides the vigorous control in transient states and the quick active reaction in overshoot and undershoots of DC-link voltage of VSI during load variation/transient state (Sekhar et al., 2016). Figure 3 demonstrates the block diagram of sliding surface design.
Calculation of In-phase current $I_{saref}$

Actual DC voltage = $V_{dc}$

Reference DC voltage = $V_{dcref}$

Step 1 Sliding Surface Design (Sekhar et al., 2016)

The LPF filtered actual $V_{dc}$ and this is compared with reference DC voltage

$$P_1 = V_{dcref} - V_{dc} \quad (2)$$

$P_1 =$ Error signal of reference and actual DC voltage

Step 2 Clauses of the sliding regime

Taking the derivative of Equation (2),

$$P_2 = \dot{P}_1 = \frac{1}{T_s} (P_1 - P_{(n-1)}) \quad (3)$$

$P_2 =$ State variable and the derivative of error

Step 3 Control law (Figure 4)

**Figure 3.** Block diagram of sliding regime.
Now the switching constraints $u$ and $v$ are selected with the help of slope of DC link voltage error

$$u = \begin{cases} +1, & \text{if } y_{P1} > 0 \\ -1, & \text{if } y_{P1} < 0 \end{cases} \quad (4)$$

$$v = \begin{cases} +1, & \text{if } y_{P2} > 0 \\ -1, & \text{if } y_{P2} < 0 \end{cases} \quad (5)$$

Now the reference DC currents

$$I_{dc_{ref}} = C P_1 u + D P_2 v \quad (6)$$

$$y = A P_1 + B P_2 \quad (7)$$

$y =$ Switching hyper plane function

A, B, C, and D are the SMC constant

Instantaneous amplitude of PCC voltage

$$V_t = \sqrt{\frac{2(v_a^2 + v_b^2 + v_c^2)}{3}} \quad (8)$$

In-Phase component of Unit templates

$$U_{sap} = \frac{V_a}{V_t} \quad (9)$$

$$U_{sbp} = \frac{V_b}{V_t} \quad (10)$$
\[ U_{scp} = \frac{V_c}{V_t} \]  

Now, the quadrature component of Unit templates

\[ U_{saq} = \frac{(-U_{sbp} + U_{scp})}{\sqrt{3}} \]  

\[ U_{sbq} = \frac{(U_{sap}\sqrt{3} + U_{sbp} - U_{scp})}{2} \]  

\[ U_{scq} = \frac{(-U_{sap}\sqrt{3} + U_{sbp} - U_{scp})}{2} \]

Now, the reference In–Phase component of active power of source current

\[ I^*_{sap} = I_{dcref}U_{sap} \]

\[ I^*_{sbp} = I_{dcref}U_{sbp} \]

\[ I^*_{scp} = I_{dcref}U_{scp} \]

The error in PCC voltage evaluated as

\[ V_{ace} = V^* - V_t \]

The PI controller creates output for keeping PCC voltage at reference value

\[ I_{acref}(k) = I_{acref}(k - 1) + K_{pa}\{V_{ace}(k) + V_{ace}(k - 1)\} + K_{ia}V_{ace}(k) \]

Where,

\[ V_{ace}(k) = K^{th} \text{ time voltage error} \]

\[ V_{ace}(k - 1) = (K-1)^{th} \text{ time voltage error} \]

\[ K_{pa} = \text{Proportional gain of PI controller, } K_{ia} = \text{Integral gain of PI controller} \]

Now, the reference quadrature –phase component of source current

\[ I^*_{saq} = I_{acref}U_{saq} \]

\[ I^*_{sbq} = I_{acref}U_{sbq} \]

\[ I^*_{scq} = I_{acref}U_{scq} \]

The total three phase reference source current is the addition of In–phase and quadrature phase component as
\[ I_{sa}^* = I_{sap}^* + I_{saq}^* \quad (23) \]
\[ I_{sb}^* = I_{sbp}^* + I_{sbq}^* \quad (24) \]
\[ I_{sc}^* = I_{scp}^* + I_{scq}^* \quad (25) \]

**ADALINE LMS CONTROL**

**Step 1. Calculation of In-phase and quadrature phase component of unit vector**

\( V_a, V_b, V_c \) are three phase PCC voltage. First it is sensed and filtered.

\[ V_t \] is obtained from equation 8.

**In-Phase component of Unit vector**

\( U_{ap}, U_{bp}, U_{cp} \) are obtained from equation 9, 10 and 11 respectively by putting the respective values of PCC voltages.

**Quadrature component of Unit vector**

\( U_{aq}, U_{bq}, \) and \( U_{cq} \) are obtained from equation 12, 13 and 14 respectively.

**Step 2. Calculation of \( Z_L(k) \) which is a part of d-axis component**

\[ Z_L(k) \]
\[ V_{dce}(k) = V_{dc ref}(k) - V_{dc}(k) \]  

\[ Z_L(k) = Z_L(k) + k_{pd} \{ V_{dce}(k) - V_{dce}(k - 1) \} + k_{id} V_{dce}(k) \]

Where \( Z_L(k) \) is the part of the d-axis component of supply current. \( k_{pd} \) and \( k_{id} \) are the proportional and integral constant of DC bus voltage.

**Step 3. Calculation of \( Z_{qv} \) which is the part of q-axis component**

Voltage error of the AC voltage at the \( k^{th} \) sampling instant:

\[ V_{te}(k) = V_t(k) - V_{tr}(k) \]  

\[ Z_{qv}(k) = Z_{qv}(k - 1) + k_{pa} \{ V_{te}(k) - V_{te}(k - 1) \} + k_{ia} V_{te}(k) \]  

**Figure 7.** Calculation of \( Z_{qv} \).

\( k_{pa} \) and \( k_{ia} \) are the proportional and integral constant of AC voltage controller.

**Step 4. Calculation of weight of the d-axis component of three phase load current**

Weight of the fundamental d-axis component \( (I_d) \) utilizes LMS control algorithm and its training through ADALINE neural network control algorithm (Singh et al., 2015)

\[ Z_{ap}(k) = [Z_{ap}(k - 1) + \epsilon (I_{La}(k) - Z_{ap}(k - 1)) U_{ap}(k)] U_{ap}(k) \]  

\[ Z_{bp}(k) = [Z_{bp}(k - 1) + \epsilon (I_{Lb}(k) - Z_{bp}(k - 1)) U_{bp}(k)] U_{bp}(k) \]  

\[ Z_{cp}(k) = [Z_{cp}(k - 1) + \epsilon (I_{Lc}(k) - Z_{cp}(k - 1)) U_{cp}(k)] U_{cp}(k) \]  

\( Z_{ap}, Z_{bp}, Z_{pc} \) are the weight of active power component of fundamental d-axis current.

Hence the average weight of fundamental d-axis component of reference supply current is

\[ Z_p(k) = (1/3) [Z_{ap}(k) + Z_{bp}(k) + Z_{cp}(k) + Z_L] \]  

\( Z_L \) = Output of DC bus voltage controller, \( \epsilon \) = convergence factor (value taken 0.01)
Figure 8. Calculation of $Z_p (k)$.

Fundamental reference d-axis ($I_d$) supply current

$$I^*_{sap} = Z_p U_{ap}, I^*_{sbp} = Z_p U_{bp}, I^*_{scp} = Z_p U_{cp}$$  \hspace{1cm} (34)

**Step5:** Calculation of weights of reactive power component of load current and reference supply current of reactive component of reference supply current.

Estimation of weight of the fundamental q-axis component ($I_q$) utilizes LMS control algorithm and its training through ADALINE neural network control algorithm (Singh et al., 2015).

$$Z_{aq}(k) = Z_{aq}(k-1) + \epsilon (I_{La}(k) - Z_{aq}(k-1) U_{aq}) U_{aq}(k)$$  \hspace{1cm} (35)

$$Z_{bq}(k) = Z_{bq}(k-1) + \epsilon (I_{Lb}(k) - Z_{bq}(k-1) U_{bq}) U_{bq}(k)$$  \hspace{1cm} (36)

$$Z_{cq}(k) = Z_{cq}(k-1) + \epsilon (I_{Lc}(k) - Z_{cq}(k-1) U_{cq}) U_{cq}(k)$$  \hspace{1cm} (37)
Figure 9. Calculation of $Z_q(k)$.

$Z_{aq}, Z_{bq}, Z_{cq}$ are the weight of active power component of fundamental d-axis current. Hence average weight of reference reactive power component of supply current

$$Z_q(k) = \frac{[Z_{qv}(k) - (Z_{qa}(k) + Z_{qb} + Z_{qc}(k))]}{3}$$  \(38\)

$Z_{qv}$ = Output of AC bus voltage controller

Fundamental reference q-axis ($I_q$) supply current

$$I_{saq}^* = Z_q U_{aq}, I_{sbq}^* = Z_q U_{bq}, I_{scq}^* = Z_p U_{cq}$$  \(39\)

Step 6: Generation of PWM signals

Figure 10. Generation of PWM signals.
The three phase reference supply current is

\[ I_{sa}^* = I_{sap}^* + I_{saq}^* \]  

(40)

\[ I_{sb}^* = I_{sbp}^* + I_{sbq}^* \]  

(41)

\[ I_{sc}^* = I_{scp}^* + I_{scq}^* \]  

(42)

These calculated reference supply currents \((I_{sa}^*, I_{sb}^*, I_{sc}^*)\) are compared with the sensed supply currents \((I_{sa}, I_{sb}, I_{sc})\) to achieve current error which produce gating signal pulses for VSI switches of DSTATCOM.

**PROPOSED ENHANCE SRF SOGI-FLL**

Here SRF without PLL has been employed in the DSTATCOM. SOGI-FLL has been adopted for synchronizing the signal (Cespedes et al., 2014). In this novel control algorithm, conventional PLL has been replaced by the SOGI-FLL. SOGI-FLL have faster reaction, less computational time and better response in eliminating power quality issues present in the non-ideal grid (Hao et al., 2017; Arya et al., 2020).

![Figure 1](image.png)

**Figure 11.** Enhanced SRF SOGI-FLL controller.
The SOGI-FLL methods have suitable steady-state and dynamic performance even if the system has varied its frequency and phase in a specified interval of time due to the impact of non-linear load. In below section, mathematical modeling of controller is designed.

MATHEMATICAL MODELING OF STANDARD SOGI-FLL

Figure 12. Standard SOGI-FLL.

Figure 12 shows the block diagram of SOGI-FLL. \( v_\alpha \) is the single phase input signal. \( \vec{v}_\alpha \) and \( \vec{v}_\beta \) are the in-phase and quadrature – phase input signal of \( v_\alpha \) respectively. \( \tilde{v}, \omega_g, \) and \( \theta \) is the amplitude, frequency and phase angle of input signal. The output of SOGI-FLL is the phase angle \( \theta \) which has been utilized in a-b-c to d-q-0 and d-q-0 to a-b-c transformation of figure 11. \( K \) and \( \lambda \) are the gain of SOGI and FLL respectively. Output signal of the SOGI-FLL are represented by \( v_\alpha(s) \) and \( v_\beta(s) \)

\[
\vec{v}_\alpha(s) = \frac{k \omega_g s^2 + k \omega_g s \omega_g^2}{s^2 + K \omega_g s + \omega_g^2} v(s) \quad (43)
\]

\[
\vec{v}_\beta(s) = \frac{k \omega_g^2 s^2}{s^2 + K \omega_g s + \omega_g^2} v(s) \quad (44)
\]
DYNAMICS OF SOGI-FLL

Initially taking the supply voltage $V_s$ is free from harmonic distortion

$$v(t) = v_{\alpha}(t) = v \cos(\omega_g t + \varphi) \quad (45)$$

Take $\omega_g t + \varphi = \theta$

Output of the SOGI for d-axis and q-axis becomes

$$\bar{v}_{\alpha}(t) = \hat{V} \cos \hat{\theta} \quad (46)$$

Figs. 13 and 14 show the frequency response of $v_{\alpha}(s)$ and $v_{\beta}(s)$ for different values of $k$ respectively.
\[ \hat{v}_\beta(t) = \hat{V} \sin \hat{\theta} \] (47)

\( \hat{v} \) and \( \hat{\theta} \) are the amplitude and phase angle of input supply voltage respectively. Assuming SOGI-FLL is in quasi locked state, \( \hat{v} \cong v, \hat{\theta} \cong \theta \). (In the steady state they are very close to \( v \) and \( \theta \) respectively). This is the basic linearization concept of FLL.

Differential equation obtained from figure

\[ \hat{v}_\alpha = \hat{\omega}_g [k(v_\alpha - \bar{v}_\alpha) - \bar{v}_\beta] \] (48)

\[ \hat{v}_\beta = \hat{\omega}_g \bar{v}_\alpha \] (49)

\[ \hat{\omega}_g = -\frac{\lambda}{v^2} (v_\alpha - \bar{v}_\alpha) \bar{v}_\beta \] (50)

Substituting the value of \( v_\alpha \) and \( \bar{v}_\alpha \)

\[ \hat{\omega}_g = \frac{\lambda}{v^2} [v \cos \theta - \hat{v} \cos \hat{\theta}] \sin \hat{\theta} \] (51)

\[ = \frac{\lambda}{2v} [v \sin(\theta - \hat{\theta}) + \hat{v} \sin 2\hat{\theta} - v \sin(\hat{\theta} + \theta)] \] (52)

Assume \( \sin(\theta - \hat{\theta}) \cong (\theta - \hat{\theta}), \hat{v} \sin 2\hat{\theta} - v \sin(\hat{\theta} + \theta) \cong 0 \)

From above assumption equation becomes

\[ = \frac{\lambda}{2v} [v(\theta - \hat{\theta})] \] (53)

\[ = \frac{\lambda}{2} [(\theta - \hat{\theta})] \] (54)

Phase angle \( \hat{\theta} \) determined from SOGI-FLL structure

\[ \hat{\theta} = \tan^{-1} \frac{v_\beta}{v_\alpha} \] (55)

Differentiating w.r.t. time yields

\[ \frac{d}{dt} \hat{\theta} = \frac{v_\alpha \hat{v}_\beta - \bar{v}_\alpha v_\beta}{v_\alpha^2 + v_\beta^2} \]
\[ \dot{\theta} = \frac{v_\alpha \dot{v}_\beta - v_\beta \dot{v}_\alpha}{\ddot{v}} \]  
(56)

Consider \( \ddot{v}_\alpha^2 + \ddot{v}_\beta^2 = \dddot{V}^2 \)

Substitute the value of \( v_\alpha \) and \( v_\beta \) in equation (56)

\[ \dot{\theta} = \frac{(\ddot{v}_\alpha^2 + \ddot{v}_\beta^2)\ddot{\omega}_g - k\ddot{\omega}_g (v_\alpha - \dot{v}_\alpha) \ddot{v}_\beta}{\dddot{V}^2} \]

Consider \((v_\alpha - \dot{v}_\alpha)\ddot{v}_\beta = -\ddot{\omega}_g \dddot{V}^2 / \lambda \)

\[ \dot{\ddot{\omega}}_g = \ddot{\omega}_g + \left( \frac{k\ddot{\omega}_g}{\lambda} \right) \dot{\ddot{\omega}}_g \]  
(57)

Coefficient of \( \frac{k\ddot{\omega}_g}{\lambda} \) i.e. \( \ddot{\omega}_g \) is grid frequency which is time dependent parameter. So, Laplace transform of equation (57) is not possible. Hence, for getting the linear model estimated coefficient of time dependent frequency is approximated to its nominal value

\[ \ddot{\omega}_g = \ddot{\omega}_g + \left( \frac{k\ddot{\omega}_g}{\lambda} \right) \dot{\ddot{\omega}}_g \]  
(58)

Now from figure, estimated amplitude for supply voltage

\[ \dddot{V} = \sqrt{\dddot{v}_\alpha^2 + \dddot{v}_\beta^2} \]  
(59)

Differentiating above equation w.r.t time yields

\[ \dddot{V} = \frac{v_\alpha \dddot{v}_\alpha + v_\beta \dddot{v}_\beta}{\sqrt{v_\alpha^2 + \dddot{v}_\beta^2}} \]

\[ \dddot{V} = \frac{v_\alpha \dddot{v}_\alpha + v_\beta \dddot{v}_\beta}{\ddot{v}} \]  
(60)

Put the value of \( \dddot{v}_\alpha \) and \( \dddot{v}_\beta \) in Equation (60)
\[
\hat{V} = \frac{k\omega_g (v_\alpha - \hat{v}_\alpha)\hat{v}_\alpha}{\hat{V}}
\]

\[
\hat{V} = \frac{k\omega_g \left[ V \cos \theta - \hat{V} \cos \hat{\theta} \right]}{\hat{V}} \cos \hat{\theta} 
\]  
(61)

\[
= \frac{k\omega_g}{2} \left[ V \cos(\theta - \hat{\theta}) + \{ V \cos(\theta + \hat{\theta}) - \hat{V} \cos(2\hat{\theta}) \} - \hat{V} \right] \quad (62)
\]

Consider \(\cos(\theta - \hat{\theta}) = 1, V \cos(\theta + \hat{\theta}) - \hat{V} \cos 2\hat{\theta} = 0\)

\[
\hat{V} \cong \frac{k\omega_g}{2} (V - \hat{V}) 
\]  
(63)

Coefficient of \(\frac{k}{2}\) i.e. \(\omega_g\) is grid frequency which is time dependent parameter. So, Laplace transform of equation (63) is not possible. For getting the linear model estimated coefficient of time dependent frequency is approximated to its nominal value

\[
\hat{V} \cong \frac{k\omega_n}{2} (V - \hat{V}) 
\]  
(64)

Based on the above linearization model, approximated magnitude of supply voltage, phase angle, and angular frequency are obtained as:

\[
\hat{V}(s) = \frac{k\omega_n/2}{s + k\omega_n/2} V(s) 
\]  
(65)

\[
\hat{\theta}(s) = \frac{(k\omega_n/2)s + \lambda/2}{s^2 + (k\omega_n/2)s + \lambda/2} \theta(s) 
\]  
(66)

\[
\hat{\omega}_g(s) = \frac{\lambda/2}{s^2 + (k\omega_n/2)s + \lambda/2} \omega_g(s) 
\]  
(67)

**Modeling of Tuning Parameters**

Characteristics equation obtained from equation (67)

\[
= s^2 + \left(\frac{k\omega_n}{2}\right)s + \frac{\lambda}{2} 
\]  
(68)
The generalized form of characteristics equation for second order system is

\[ S^2 + 2\varepsilon \omega_n^2 s + \omega_n^2 = 0 \quad (69) \]

On comparing equation (68) and (69)

\[ 2\varepsilon \omega_n^2 = k \frac{\omega_n}{2}, \text{ where } \varepsilon = \text{ damping factor, } \omega_n^2 = \frac{\lambda}{2}, \text{ where } \omega_n = \text{ natural frequency, } \omega_n = \text{ nominal value of grid frequency.} \]

Consequently, only two values \( k \) and \( \lambda \) i.e. SOGI gain and FLL gain to be optimized to best value so that the optimum tradeoff between settling time and overshoot will occur (Hao et al., 2017; Wen et al., 2016). From frequency response of in–phase and quadrature – phase supply voltage it is quite clear that \( \varepsilon = 0.707(\text{or } 1/\sqrt{2}) \) gives the best tradeoff between settling time and overshoot. So \( \varepsilon = 0.707(\text{or } 1/\sqrt{2}) \) is considered.

\[ \omega_n^2 = \frac{\lambda}{2}, \quad \lambda = 2\omega_n^2 \]

\[ \omega_n = \frac{k \omega_n}{4\varepsilon} \quad (70) \]

\[ \lambda = \frac{k^2 \omega_n^2}{8\varepsilon^2} \quad (71) \]

Put \( \varepsilon = 1/\sqrt{2} \)

\[ \lambda = \frac{k^2 \omega_n^2}{4} \quad (72) \]

From equation (72), it is quite obvious that \( k \) and \( \lambda \) are relation with each other. In this work we have taken \( k = 1/\sqrt{2}, \lambda = 12337 \)
Table 1. SOGI Parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOGI gain, $k$</td>
<td>$1/\sqrt{2}$</td>
</tr>
<tr>
<td>FLL gain, $\lambda$</td>
<td>12337</td>
</tr>
<tr>
<td>Frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Nominal angular frequency $\omega_n$</td>
<td>$2\pi 50$ rad/sec</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSIONS

The three H-bridge inverter based DSTATCOM under synchronous reference frame, sliding mode control, ADALINE LMS and proposed Enhance SRF SOGI FLL has been modeled in MATLAB/Simulink. MATLAB 2018a version has been employed to model the simulation with Ode23t solver. Simulation time of 1.6s has been considered for the dynamic result for all controllers. After execution, following observations are analyzed:

Compensation behavior of DSTATCOM under Dynamic load condition from [0-0.4]s

![Figure 15. Performance of DSTATCOM under SRF controller.](image-url)
Simulation results of DSTATCOM with the above four control techniques are certified using MATLAB/SIMULINK. The results have been observed under various loading conditions such as linear, non-linear, unbalanced etc.

**Figure 16.** Performance of DSTATCOM under sliding mode controller.

**Figure 17.** Performance of DSTATCOM under ADALINE LMS controller.
The DSTATCOM is in uncompensated mode during \( t = [0 \text{ s} - 0.2 \text{ s}] \) and after, at \( t = 0.2 \text{ s} \), DSTATCOM comes into operation. Figs. 15 to 18 represent the performance evaluation of source current, DC capacitor voltage, DSTATCOM current and load current by SRF, SMC, ADALINE LMS and proposed Enhance SRF SOGI-FLL controller respectively. In above figures, when DSTATCOM is in operation, the waveforms of source current become sinusoidal. Load current \( I_L \) is non-sinusoidal throughout the period and contains the odd and even harmonics. Due to transient in the system, the DC voltage regulations of 700V have been achieved at different time for each controller. In SRF, SMC, ADALINE LMS and proposed Enhance SRF SOGI-FLL controller, DC voltage regulation occurs at \( t = 0.31 \text{ s}, 0.28 \text{ s}, 0.25 \text{ s} \) and \( 0.21 \text{ s} \) respectively. This indicates that DC voltage regulates fast in proposed Enhance SRF SOGI-FLL controller.

**Compensation behavior of DSTATCOM under dynamic load condition from [0.4-1]s**

In this section, dynamic behaviors of DSTATCOM have been performed during \( t = [0.4 \text{ s} - 1 \text{ s}] \). Non-linear and unbalanced linear load have been considered to observe compensation performance of DSTATCOM with its several control techniques. Figs. 19 to 22 represent the performance evaluation of DSTATCOM by SRF, SMC, ADALINE LMS and proposed...
Enhance SRF SOGI-FLL controller respectively. During the interval $t = [0.4s-0.6s]$ only linear load has been applied, interval $t = [0.6s-0.9s]$ only non-linear load has been inserted and interval $t = [0.9s-1s]$ again non-linear load has been disconnected and only linear load has been connected. During $t = [0.4s-0.6s]$, load current and source current are sinusoidal, in interval $t=[0.6s-0.9s]$, load current is non-sinusoidal due to insertion of non-linear load and source current is sinusoidal due to compensation effect of DSTATCOM. DC voltage regulation occurs at approximately 700V but, during insertion and removal of loads, a huge increase in magnitude of capacitor voltage occurs in the three controllers except proposed Enhance SRF SOGI-FLL controller.

![Performance of DSTATCOM under SRF controller.](image19)

**Figure 19.** Performance of DSTATCOM under SRF controller.

![Performance of DSTATCOM under sliding mode controller.](image20)

**Figure 20.** Performance of DSTATCOM under sliding mode controller.
This increase in DC capacitor voltage will suddenly increase the reactive power demand and creates burden in the source side. It has been also observed that DSTATCOM current is sinusoidal for linear load while DSTATCOM current is non-sinusoidal for non-linear load.

**Compensation behavior of DSTATCOM under dynamic load condition from [1s-1.6s]**

In this section, dynamic behaviors of DSTATCOM have been studied during $t = [1s-1.6s]$. Figs 23-26 represent the performance of DSTATCOM by SRF, SMC, ADALINE LMS and proposed enhance SRF SOGI-FLL controller respectively. During $t = [1s-1.2s]$, linear load has been employed hence wave form of source current, DSTATCOM current, and load current are sinusoidal. In the interval $t = [1.2s-1.4s]$, non-sinusoidal waveform occurs in load current and DSTATCOM current while sinusoidal waveform of source current has been
achieved due to DSTATCOM compensation.

Figure 23. Performance of DSTATCOM under SRF controller.

Figure 24. Performance of DSTATCOM under sliding mode controller.

Figure 25. Performance of DSTATCOM under ADALINE LMS controller.
Figure 26. Performance of DSTATCOM under proposed Enhance SRF SOGI-FLL controller. DC voltage regulations under proposed enhance SRF SOGI-FLL controller is 700V, but in case of SRF, SMC and ADALINE LMS, DC voltage regulation has been accomplished at 702V, 698V, 697V respectively.

Reactive power analysis of DSTATCOM under various control algorithms

Figs. 27 to 30 represent the performance evaluation by SRF, SMC, ADALINE LMS and Enhanced SRF SOGI-FLL controller respectively in terms of real and reactive power analysis. During interval t= [0s -0.2s], reactive power demand from load is increasing and after 0.2s, it comes to nearly “0” due to compensation effect of DSTATCOM. When non-linear load has been introduced and DSTATCOM is in “on” condition then the reactive power demand by the load is full filled by the DSTATCOM, hence there is no impact on the source side and it gives the null reactive power at that time. In proposed controller, the reactive power is exactly at “0”, but in conventional controllers, reactive power is somewhat not zero but tendency to reach zero. Figure 31 shows the grid voltage and current waveform. At t = 0s to 0.2s, when DSTATCOM is not in operation, source current is non-sinusoidal and out of phase with voltage. After t = 0.25s, when DSTATCOM starts compensation, source current is sinusoidal and in-phase with the source voltage, which shows power factor improvement on supply side.
Figure 27. Reactive power analysis of DSTATCOM under SRF.

Figure 28. Reactive power analysis of DSTATCOM under SMC.

Figure 29. Reactive power analysis of DSTATCOM under ADALINE LMS.
Figure 30. Reactive power analysis of DSTATCOM under proposed enhance SRF SOGI FLL.

Figure 31. Grid voltage and current analysis under proposed enhance SRF SOGI FLL.
Table 2. Obtained THD and Power factor data.

<table>
<thead>
<tr>
<th>Control philosophies</th>
<th>Source current</th>
<th></th>
<th></th>
<th>Power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_{sa}$</td>
<td>$I_{sb}$</td>
<td>$I_{sc}$</td>
<td>THD (%)</td>
</tr>
<tr>
<td>SRF</td>
<td>3.44</td>
<td>3.56</td>
<td>3.28</td>
<td>0.92</td>
</tr>
<tr>
<td>SMC</td>
<td>3.03</td>
<td>3.34</td>
<td>3.53</td>
<td>0.95</td>
</tr>
<tr>
<td>ADALINE LMS</td>
<td>1.81</td>
<td>1.93</td>
<td>1.93</td>
<td>0.97</td>
</tr>
<tr>
<td>Enhance SRF SOGI FLL</td>
<td>1.32</td>
<td>1.46</td>
<td>1.23</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2 depicts the comparative analysis of source current THD and power factor in view of conventional and proposed controllers. Based on Table 2, it has been found that less source current THD has been achieved in proposed Enhance SRF SOGI FLL. Moreover, unity power factor has been occurred in Enhance SRF SOGI FLL. Table 3 indicates about comparative features of different control schemes adopted in the DSTATCOM.

Figure 32 shows the comparative power quality features of different control algorithms in chartable forms. To visualize the performances of power factor and THD, maximum value of DC voltage regulation has been taken as 7 instead of 700V. In this figure, the proposed controller represents better power quality performances.
### Table 3. Comparison between SRF, SMC, ADALINE LMS and Enhance SRF SOGI FLL.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SRF</th>
<th>SMC</th>
<th>ADALINE</th>
<th>Enhance SRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computational Burden</td>
<td>Complex calculation</td>
<td>Complex calculation</td>
<td>Complex calculation</td>
<td>Simple calculation</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Complexity</td>
<td>More</td>
<td>Less</td>
<td>Less</td>
<td>Very less</td>
</tr>
<tr>
<td>Operational time</td>
<td>More</td>
<td>More</td>
<td>Less</td>
<td>Very less</td>
</tr>
<tr>
<td>Synchronization with grid</td>
<td>Present but conventional PLL have some disadvantages</td>
<td>Absent</td>
<td>Absent</td>
<td>Present with excellent characteristics</td>
</tr>
<tr>
<td>Harmonic compensation</td>
<td>Good (Well within the IEEE-519)</td>
<td>Good (Well within the IEEE-519)</td>
<td>(Well within the IEEE-519)</td>
<td>Excellent (Well within the IEEE-519)</td>
</tr>
<tr>
<td>Dynamic behavior</td>
<td>It takes more time to stable</td>
<td>It takes less time to stable</td>
<td>It takes less time to stable</td>
<td>It takes negligible time to stable and acts very fast in dynamic situation</td>
</tr>
</tbody>
</table>
Figure 32. Chartable representations of comparative features.

CONCLUSION

The comparative studies of conventional i.e. SRF, SMC, ADALINE LMS and proposed i.e. Enhance SRF SOGI FLL control based H-bridge DSTATCOM in three-phase four-wire distribution system have been elaborated in terms of power quality improvement. The performances of DSTATCOM have been tested under various dynamic loading conditions. On the basis of extensive simulation studies, it has been found that the above controllers are capable to restrict THD of the source currents as per IEEE-519 standard. Moreover, these controllers are also compensating the reactive power, balancing the voltages and currents phases, and improving the power factor on the supply side. In respect to comparison among these controllers, it has been found that the proposed Enhance SRF SOGI FLL performs the best power quality improvement features.
REFERENCES


