Reference Waveform Generation Techniques for Series Compensators

R. B. Sharma

Abstract: ***Series compensators are implemented in power system to overcome the power quality issues like voltage dip (sag) and voltage swell. Series compensators such as Dynamic Voltage Restorer have demonstrated their effectiveness in enhancement of power quality. The control techniques for these devices underwent the progressive changes as per industry needs. Control techniques can be majorly classified as frequency domain (s-domain) and time-domain techniques. In the time-domain algorithm reference signal generation is important step for successful implementation of algorithm. In this paper the two reference generation methods namely Synchronous Reference Frame (SRF) method and Unit Vector template (UVT) method are analyzed and compared for their suitability considerations.***

Keywords: ***phase lock loop, Power quality Series compensator, Synchronous Reference Frame, Unit Vector template***

I. INTRODUCTION

Application of power electronics have led to the number of Power Quality (PQ) problems such as voltage and current harmonics, voltage dip (sag), swell, flicker and transients that persists in modern power system. These PQ issues are of concern to power system engineers as they are responsible for distortion of supply voltage and current waveform. The customers suffer the economic loss specifically industrial customers as PQ events affect the normal operation of sensitive electrical loads such as electric drives, computer systems, and industrial electronic controllers.

From various PQ disturbances, voltage dip occurs most frequently and hence is responsible majorly for economical losses to customer. IEEE standard 1159 defined voltage sag as decrease in root mean square value (r.m.s.) value of supply voltage between 10% to 90% of nominal system voltage at the power frequency for duration of 0.5 cycle to 1 minute is called voltage sag. Similarly, increase in r.m.s. value of supply voltage above 110% of nominal system voltage at the power frequency for duration of 0.5 cycle to 1 minute is called voltage swell [1]. The events in power system that cause voltage dip and swell are starting of heavy three-phase loads, balanced and unbalanced faults, switching of reactive power source, in-rush transformer current, switching in or out of single phase load [2], [3].

For mitigation of PQ disturbances at distribution level in power system the power electronics based control system was designed. This technology was termed as 'Custom Power Device' (CPD). CPDs are categorized as series, shunt devices and combination of these both. For mitigation of issues like voltage sag and swell series compensators are implemented in power system. These compensators will provide steady voltage to load irrespective of source terminal voltage.

Dynamic Voltage Restorer (DVR) is series compensator and has demonstrated its effectiveness in enhancement of power quality. DVR injects voltage of proper magnitude and frequency in series of supply voltage and hence restores the load voltage to desired amplitude on occurrence of sag [4], [5]. The control techniques for these devices underwent the progressive changes as per industry needs. Control techniques can be majorly classified as frequency domain (s-domain) and time domain (t-domain) techniques. The t-domain algorithms are more preferred over s-domain algorithms as they are less complicated for implementation in hardware, less dependent on system component parameters and real-time feedback signals are utilized. In the time-domain algorithm reference waveform generation is critically important for successful implementation of algorithm. Synchronous Reference Frame (SRF) method, Unit Vector template (UVT), symmetrical component method, reactive power theory based method are commonly implemented t-domain methods for DVR control [6-9]. To compensate voltage sag and harmonics proposed a versatile device named as static conditioner [10]. The genetic algorithm fuzzy logic based DVR suggested in [11] for compensation of balanced and unbalanced sag and swell on load side. The compensation using static var generator and DVR in low voltage system is as proposed in [12]. An innovative and cost effective DVR solution for low voltage smart distribution system is presented in [13]. An adaptive fuzzy based DVR control methodology is implemented in [14].

In this paper the reference generation algorithms namely SRF method and UVT method are analyzed and compared for their suitability considerations. In Section II the architecture and types of DVR is introduced. The reference generation algorithm steps for SRF and UVT techniques are described in Section III. In Section IV the comparative study and analysis is explained. MATLAB/Simulink environment is utilized to analyze the effectiveness of these algorithms.

II. DVR ARCHITECTURE AND TYPE

The DVR as a series compensator have effectively been implemented in the field to mitigate the voltage related PQ issues and hence will be considered in this paper. DVR is supposed to insulate the critical load in power system from PQ disturbances.

Revised Manuscript Received on October 15, 2019
* Correspondence Author
R.B. Sharma, Electrical Engineering Department, Government college of Engineering, Amravati, India. Email: drrbs1974@gmail.com

A. Basic DVR Structure

DVR composed of two circuits namely:

- **Power circuit:** It consists of transformers for voltage injection, voltage source converter (VSC) for waveform generation and element for D.C. energy storage.
- **Control circuit:** It consists of system for electrical parameter monitoring, reference signal generation processing unit and controller to control VSC output. Fig. 1 represents equivalent scheme for single-phase DVR.

In DVR, transformer is in series with supply line which are fed by VSC that serves as voltage source. Thus these transformers isolate supply lines and DVR and hence are also called isolation transformer. The energy source for VSC is D.C. storage capacitor (C_{dc}). The combination of inductance of injection transformer winding inductance (L_f) and filter capacitor (C_f) forms the low pass filter which is connected across secondary of isolation transformer in series with the switching resistor (R_{sw}).

Thus, load terminal phase voltage (V_L) is the phasor addition of source phase voltage (V_s) at the point of common coupling (PCC) and DVR injected voltage (V_{inj}).

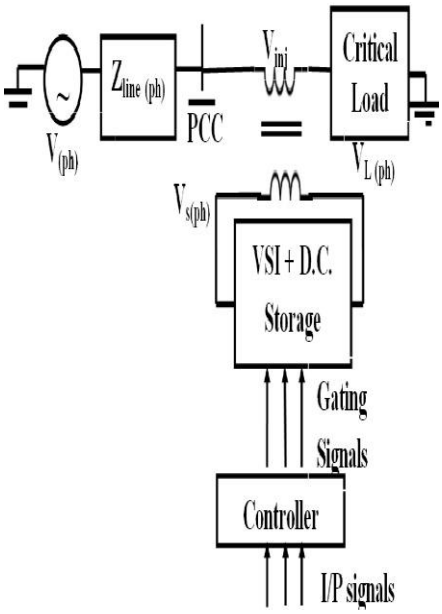

Fig. 1 Single phase DVR schematic

The load phase voltage ($V_{L)}$ can be given by equation (1)

$$V_L = V_s + V_{inj} \quad (1)$$

B. DVR Types

The type of DVR is classified on the basis of D.C. energy source utilized for injecting the required voltage by DVR.

- **Battery-supported DVR:**

If active power is required for compensation by DVR then the battery is to be utilized for DVR as D.C. energy source. As shown in fig.2 and fig.3, the in-phase and pre-sag compensation method is utilized. In these methods the V_{inj} is at non-quadrature angle with respect to I_s, hence battery is used as energy storing element.

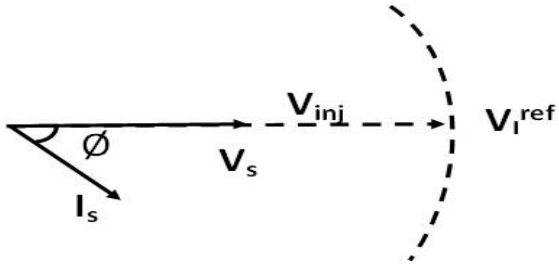

Fig. 2 In-phase compensation

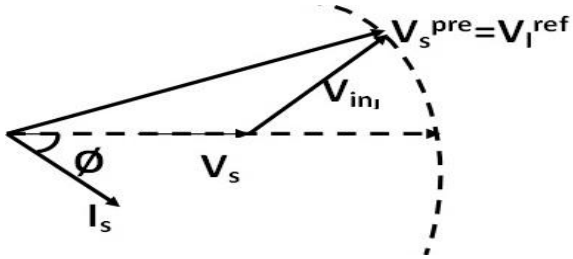

Fig. 3 Pre sag compensation

- **Self-supported DVR:**

As shown in fig. 4 in this method the V_{inj} is at quadrature with respect to I_s, only reactive power is required for compensation by DVR. Hence no external D.C. storage element is required. D.C. link capacitor itself works as energy storage element. Sometimes the combination of these methods is implemented, to optimize the utilization of DVR energy source [15].

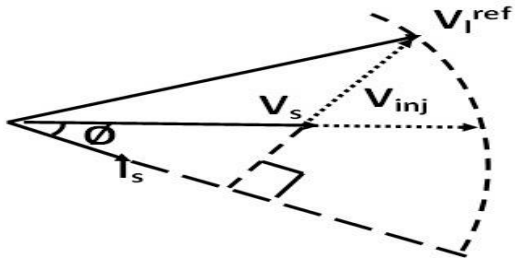

Fig. 4 In-quadrature compensation

III. TIME DOMAIN ALGORITHMS

As self-supported DVR do not require any D.C. storage element, it is economical solution for PQ issue mitigation. Hence, self-supported type DVR is considered to explain the reference waveform generation methods.

A. Synchronous Reference Frame algorithm

SRF technique had been popularized for the development of control strategies due to its robustness and less complexity in its application. SRF is based on transformation of rotating frame vectors into stationary frame vectors using the Park's transformation. For self-supported type DVR the SRF control algorithm has been referred from [6].

The generalized steps of this algorithm are as follows:

i) Terminal voltage signals (v_{sa}, v_{sb}, and $v_{sc)}$ at the point of common coupling (PCC) are transformed into the d-q components (V_d and V_q) using the Park's transformation is as given in equation (2);

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \sin\theta & \sin(\theta-120^0) & \sin(\theta+120^0) \\ \cos\theta & \cos(\theta-120^0) & \cos(\theta+120^0) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (2)$$

In equation (2) the angle θ is computed by Phase-lock-loop (PLL). For fundamental extraction θ is computed by PLL over v_{sa}, v_{sb}, and v_{sc}.

ii) The signals V_{d1} and V_{q1} are then passed through low-pass filter (LPF) to obtain pure steady signals (V_{d_filt} and V_{q_filt}).

iii) The filtered signals are then re-constructed back into fundamental three-phase signals using inverse Park's transform as shown in equation (3).

$$\begin{bmatrix} V_{af} \\ V_{bf} \\ V_{cf} \end{bmatrix} = \begin{bmatrix} \sin(\theta) & \cos(\theta) \\ \sin(\theta-120^0) & \cos(\theta-120^0) \\ \sin(\theta+120^0) & \cos(\theta+120^0) \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \quad (3)$$

iv) The fundamental sinusoidal signals of equation (3) are then passed through Park's transformation of equation (2) but with θ computed by PLL over line currents (i_{sa}, i_{sb}, and i_{sc}). The conversion results into D.C. signals V_{d2} and V_{q2}.

The voltage across C_{dc} , V_{dc}, is taken as a feedback signal to determine the error e_{dc} as in equation (4).

$$e_{dc} = V_{dc}^{ref} - V_{dc} \quad (4)$$

v) e_{dc} is further passed over discrete proportional-integral (PI) controller to obtain signal V_{loss} which is a measure of the active power loss component.

$$V_{loss}e = K_p e_{dc} + K_i \sum e_{dc} \quad (5)$$

vi) Thus, the reference d-q components are obtained using the equation (6) as;

$$V_d^{ref} = V_{d2} - V_{loss}$$
$$V_q^{ref} = \sqrt{(V_m^{ref})^2 - (V_d^{ref})^2} \quad (6)$$

Where; V_m^{ref} is the reference peak load voltage.

By using equation (3), V_d^{ref} and V_q^{ref} component can further are inversely transformed into reference signals of three phases namely V_a^{ref}, V_b^{ref}, and V_c^{ref}.

B. Unit Vector Template algorithm

UVT based method is another simplified reference generation time-domain algorithm implemented for control of DVR. The algorithm is referred from [7].

The steps for this algorithm are described as follows:

i) The line current signals (i_{sa}, i_{sb}, and i_{sc}) are taken to compute the in-phase unit vectors and quadrature unit vectors as shown in equation (7) and quadrature unit vectors as shown in equation (8);

$$\begin{bmatrix} P_a \\ P_b \\ P_c \end{bmatrix} = \frac{1}{(i_s)_m} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} q_a \\ q_b \\ q_c \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -\frac{2}{\sqrt{3}} & \frac{2}{\sqrt{3}} \\ \sqrt{3} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ -\sqrt{3} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} p_a \\ p_b \\ p_c \end{bmatrix} \quad (8)$$

Where $(i_s)_m$ is the amplitude of supply current and is given by;

$$(i_s)_m = \sqrt{i_{sa}^2 + i_{sb}^2 + i_{sc}^2} \quad (9)$$

ii) The error e_{dc} of equation (4) will be passed over PI controller as in equation (5) to give the in-phase element of the reference voltage (V^{ref}_d).

iii) Similarly, the quadrature component is calculated by passing the error between reference load peak and actual load peak through the PI controller.

$$e_m = V_m^{ref} - V_m$$
$$V_q^{ref} = K_p e_m + K_i \sum e_m \quad (10)$$

Thus, reference load voltages (v_a^{ref}, v_b^{ref}, and v_c^{ref}) are obtained as in equation (10);

$$\begin{bmatrix} v_a^{ref} \\ v_b^{ref} \\ v_c^{ref} \end{bmatrix} = v_d^{ref} \begin{bmatrix} p_a \\ p_b \\ p_c \end{bmatrix} + v_q^{ref} \begin{bmatrix} q_a \\ q_b \\ q_c \end{bmatrix} \quad (11)$$

IV. ANALYSIS AND DISCUSSION

The steps discussed for SRF and UVT techniques are implemented for DVR using the MATLAB/Simulink environment. The signal output of these algorithm steps are considered for analysis of advantages and disadvantages these algorithms.

i) In SRF algorithm, for fundamental component extraction, steady state signals V_{d1} and V_{q1} are passed through low-pass filter. Thus filtering of these signals to remove the chattering and obtaining pure D.C. signal will not result into the phase delay. The distorted and filtered D.C. signals are as shown in fig. 5.

Hence the fundamental abstracted by reverse transformation is also sinusoidal. In fig. 6 distorted source signal (v_{sa}) and fundamental extracted signal by reverse transformation is shown for phase a.

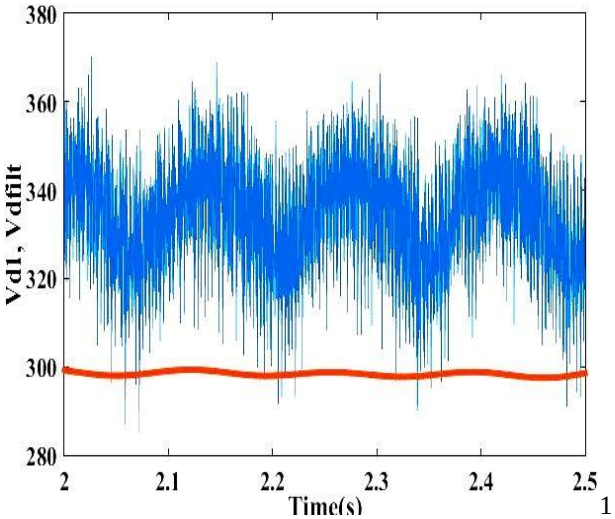

Fig. 5 V_{d1} component filtered in SRF method

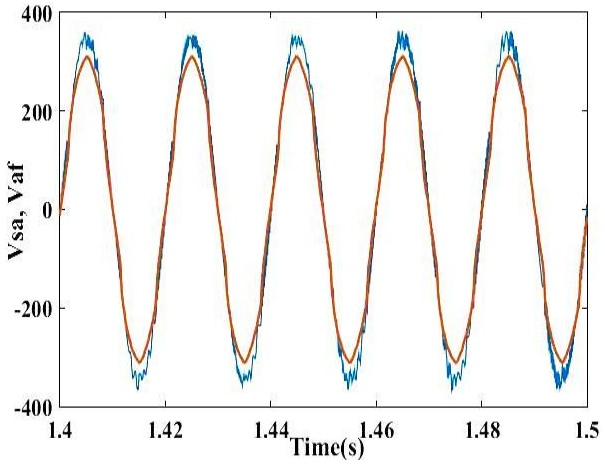

Fig. 6 Fundamental component extraction in SRF method

ii) In case of SRF method the phase angle θ is required for the transformation which necessitates the use of PLL. However, for UVT method determination of θ is not needed as in-phase and quadrature unit vectors are determined from current feedback signals and transformation matrix.

iii) For UVT method, if the line current signals (i_{sa}, i_{sb}, and i_{sc}) are distorted due to harmonics, the derived unit vectors are also distorted. The filtering of these signals results into the phase delay which further hampers the real-time compensation process. The distorted and filtered unit vector for i_{sa} is as shown in fig.7.

iv) The phase-jumps in current signal due to sudden fault in system may again lead to distortion of unit vectors in UVT technique which is avoided due to phase locking of PLL in SRF method.

v) PI controller tuning is critical for reference signal generation. In UVT technique two PI controllers are required to regulate the magnitude of in-phase voltage vectors and quadrature voltage vectors, SRF method require only one PI controller for computing the active loss component (V_{loss}).

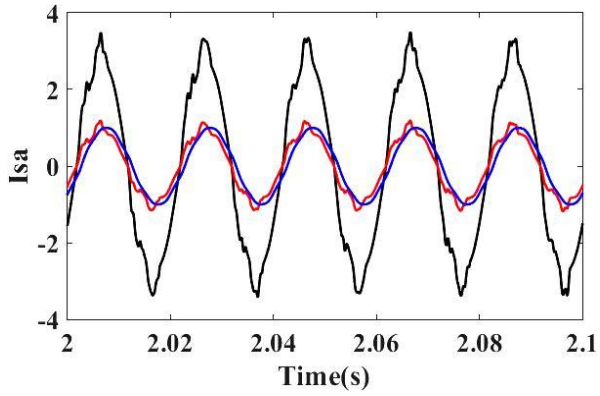

Fig. 7 Phase delay introduced in UVT method

Thus, comparatively SRF algorithm is more resistant to tuning of PI as compared to UVT algorithm. The comparison for various parameters for SRF and UVT method is as shown in Table 1.

Table- I: Comparison of UVT and SRF method

Case	SRF method	UVT method
No. of feedback signals	7	7
No. of PI controllers	1	2
Phase angle (θ)	Required	Not required
No. of PLL	2	Not required
Phase angle delay	Not introduced	Introduced

V. CONCLUSION

To mitigate the voltage PQ issues like voltage dip and swell, series compensator such as DVR is useful. For the reasons like no requirement of PLL for reference generation for UVT algorithm, it is advantageous over SRF algorithm. However, under the circumstances like distorted current, the UVT algorithm results in distorted reference waveform whereas in SRF method fundamental extraction is beneficial for pure reference generation.

REFERENCES

1. IEEE Standards Office, "IEEE Recommended Practice for Monitoring Electric Power Quality", IEEE Standard 1159-2005.
2. C. Sankaran, *Power Quality*, CRC Press, September, 2019.
3. M. B. Tasare, G. M. Dhole, S. S. Jadhao, R. B. Sharma, "A simplified algorithm for sag and harmonic mitigation using DVR," International conference on Computing, Communication, Control and Automation (ICCUBEA), 2017.
4. R. C. Dugan, M. F. Mcgranaghan, S. Santo, H. W . Beaty, *Electrical Power Systems Quality* McGraw-Hill Education, 2012.
5. N. H. Woodley, L. Morgan, and A. Sundaram, "Experience with an inverter-based dynamic voltage restorer," *IEEE Trans. on Power Delivery*, vol. 14, July 1999, pp. 1181–1186.
6. Parag Kanjiya, Bhim Singh, Ambrish Chandra, Karmal Al-Haddad, "SRF theory revisited to control self-supported dynamic voltage restorer (DVR) for unbalanced and nonlinear loads," *IEEE Trans. On Industry Applications*, vol. 49, October 2013, pp. 2330-2340.
7. Bhim Singh, P. Jayaprakash, D. P. Kothari, A. Chandra, Karmal- , Al-Haddad, "New control algorithm for capacitor supported DVR," *Journal of Electromagnetic Analysis and Applications,vol.3, July 2011, pp. 277-286.*

8. I. M. Marei, E.F.El-Saadany, M. M. A. Salama, "A new approach to control DVR based on symmetrical components estimation," *IEEE Trans. on Power Delivery*, vol. 22, October 2007, pp. 2017-2024.
9. C .Guodong, M. Zhu, X. Cai, "Medium-voltage level dynamic voltage restorercompensation strategy by positive and negative sequence extractions inmultiple reference frames," *IET Power Electronics*, vol. 7, July 2014, pp.1747–1758.
10. J.R.Perez, A.G.Cerreda, J.L. Zamora, E.Acha, "Trouble shooting a digital repetitive controller for a versatile dynamic voltage restorer," *International Journal of Electrical Power Energy System* vol. 57, May 2014, pp. 105–115.
11. C. K. Subryamanam, K. Selvi,"Real coaded Genetic Algorithm optimized fuzzy logic controlled EMFP based dynamic voltage restorer for reparation of voltage disturbances in distribution system," *International Journal of Hydrogen Energy*, vol. 42, January 2017, pp. 603–613.
12. R. Sun, H. Qie, X. Yuan, S. Luo, W. Gu,"Voltage sag improvement using DVR and SVG in a power system," In Proceedings China International Conference on Electricity Distribution, CICED 2016.
13. H. Hefaz, R. Farnanda, "Dynamic voltage conditioner, a new concept for smart low voltage distribution system," *IEEE Trans. on Power Electronics*, vol. 20, November 2017, pp. 7582–7590.
14. N. Mallick, V. Mukharjee,"Self tuned fuzzy propronal integral compensated zero/minimum active power algorithm based dynamic voltage restorer," *IET Generation, Transmission and Distribution Trans. on Power Electronics*, vol. 12, June 2018, pp. 2778–2787.
15. A. M. Rauf, V. Khadkikar, "An enhanced voltage sag compensation scheme for dynamic voltage restorer," *IEEE Trans. Industrial Electronics*, vol. 62, May 2015, pp. 2683–92.

AUTHORS PROFILE

Rajesh Bhikulal Sharma obtained his B.E. degree in Electrical Engineering and M.E. (E.P.S.) from Shri Sant Gajanan Maharaj College of Engineering Shegaon, S.G.B. University Amravati, India 1997 and 2001 respectively. He received Ph.D. degree in Electrical Engineering from Amravati University, India. He is a member Institution of Engineers (India) and Indian Society for Technical Education. He authored more than 10 research papers in National and International Journals. His research includes transient power system stability, smart grid and wide area measurement system.