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Synchronverter: A Comprehensive Review of Modifications, Stability Assessment, Applications and Future Perspectives

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ABSTRACT The increase in the penetration of renewable energy sources (RES) has reduced the effective inertia of the power system dominated by synchronous machines. The reduction in inertia has paved the way to the development of inertia emulation techniques, which complements the increased penetration of RES. The synchronverter technology is one among the virtual inertia emulation techniques which resembles close to the synchronous machine. The advancements in control and adaptations of synchronverter for various applications demand a comprehensive yet critical review. Thus, the main objective of this paper is to present a critical review of synchronverter technology which could increase the inertial response of RES. A critical analysis of modifications made to original synchronverter and the stability assessment techniques is presented. The effect of parameter variation on stability and dynamic performance is brought out as a decision matrix by analysing the movement of eigenvalues presented in various works. Towards the end, a synoptic overview is presented to depict the research trend and emphasize the domain which requires further attention. Furthermore, a brief discussion of the research gaps perceived during the phase of review is presented to leverage future research in the field.

INDEX TERMS Energy storage, frequency stability, microgrid, power converter, renewable energy, synchronverter, virtual inertia, virtual synchronous generator.

I. INTRODUCTION

The thrust towards reducing carbon emission with the sustainable energy generation has increased the penetration of renewable energy sources (RES) into the power system. The economic and technical viability of RES has contributed to the transition of the power system from centralized generation to distributed generation (DG). The centralized generation is dominated by synchronous machines (SM) whose inertia plays a vital role in the instantaneous balancing of generation and demand. The kinetic energy stored in the rotor of SM is proportional to the rotor inertia and it is released or absorbed during power imbalance in the grid.

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However, the concept of DG has reduced the effective inertia of the power system while trying to eliminate losses in the centralized power generation. The main cause for the decline in inertia is the absence of a rotating component in the static RES and energy storage systems (ESS) (*see* Fig.1). Although the variable speed wind and hydro turbines have rotational inertia, the effective inertia contribution is almost zero (hidden inertia) [1], [2]. The power converter decouples the sources from the grid and eliminates the frequency-dependent nature of rotating machines. The potential degradation in system inertia leads to an increase in the rate of change of frequency (ROCOF) and frequency nadir [3]. The former leads to accidental operation of ROCOF relay and the latter triggers the automatic under frequency load shedding even for a small variation in load [4].

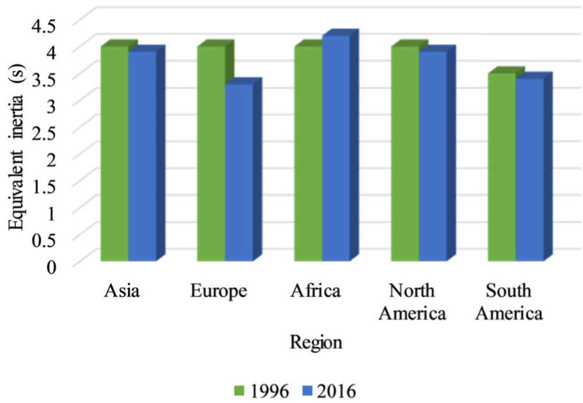

FIGURE 1. Reduction in equivalent inertia from 1996 to 2016 in different regions [3].

Besides that, the paradigm of system stability changes with the increased penetration of power converters in the interconnected power system [5]. The challenges in operating a microgrid without synchronous machines (SM) [6] also applies to the interconnected system with higher RES penetration. There can be two possible solutions to address these issues: one is to restructure the operation and control of the whole power system, second is to mimic the behaviour of SM which dominates the present power system. The former is an infeasible solution and hence it has been ruled out. So, the researchers around the globe tried to develop control strategies for power converter to make it behave like an SM.

Firstly, the demand to induce frequency dependency into power converters had led the way for droop controlled converters [7]. The effect of droop coefficient emulates the frictional torque component of SM but does not exhibit the inertial response. Subsequently, several strategies have been developed to replicate the inertial response of SM. The strategies include virtual synchronous machine (VISMA) [8], [9], Kawasaki heavy industries topology [10], Ise lab's topology [11], virtual synchronous generator (VSG) [12] and synchronverter (SV) [13]. A critical comparison between popular virtual inertia emulation techniques and synchronverter is presented in Table 1 to have better insight.

Among the various strategies, complemented by its detailed mathematical model, the synchronverter exhibits transient behaviour which is identical to SM. The synchronverter includes all the critical properties of SM like rotor inertia, oscillation damping and self-synchronization, which hold the stability of large power systems. Meanwhile, it also exhibits undesired characteristics like hunting, loss of excitation, loss of synchronism which are prevalent in SM. The factors which have been considered and yet to be considered for modelling of synchronverter and its analogy with SM are presented in Table 2.

Furthermore, the current-controlled converters used for RES integration is perceived as a static-source with zero inertial contribution from the grid side. The reduction in effective inertia can be compensated through the increased penetration of synchronverters in the power system. The cumulative effect of spatially dispersed synchronverters mimics the transient behaviour of a large SM. Meanwhile, it gives rise to new ancillary services which can be traded (*see* Fig. 2). Due to these advantages, the synchronverter has received keen attention from the researchers around the globe for grid integration of RES and operation of autonomous microgrids.

Previously, various reviews have been carried out to emphasize the need for virtual inertia [14], [15], compare various inertia emulation techniques [16], [17] and investigate the operation of VSGs in a weak grid [18]. However, a critical and comprehensive review of synchronverter in specific is yet to be reported to the best of authors knowledge. Thus, a critical review on modifications to original synchronverter, stability aspects, the effect of parameter variation and deployment of synchronverter for various applications is presented. Furthermore, a synoptic review is presented to analyse the current trend along with an elaborate discussion on future perspectives. Hence, this paper would serve as a reference and leverage future research on synchronverter control and its applications in the modern power system.

The paper is organized as follows: the empirical and small-signal modelling of original synchronverter is presented in section II, followed by the various adaptation of synchronverter in section III. The stability analysis approaches of synchronverter and deployment of synchronverter for different applications are presented in section IV and V respectively. Finally, a brief overview and discussion on future research direction are presented in section VI and the paper is concluded in section VII.

II. SYNCHRONVERTER

The energy storage element in the DC bus of the power electronic fed distributed generation has been used to mimic the inertial response of SM. The original synchronverter model has a power block and a control block to emulate the dynamic behaviour of SM (*see* Fig. 3). An LCL filter with inductances L_{f1}, L_{f2} and capacitance C_f is used to interface synchronverter with the grid having inductance L_g and resistance R_g. The grid current I_g and voltage V_g are used as feedback to regulate the real and reactive power output of synchronverter.

A. ORIGINAL SYNCHRONVERTER

The modelling and control of original synchronverter are presented to lay the basis for better understanding of stability assessment techniques and the effect of parameters on the system stability.

1) EMPIRICAL MODELLING

The original synchronverter strategy has been derived from the dynamic model of the round rotor SM with distributed stator windings having self and mutual inductances L and M respectively. The rotor is assumed to have a single pole pair and concentrated windings with self and mutual inductances L_f and M_f respectively [13]. However, the effects of damper winding and magnetic saturation have been neglected to simplify the control structure. The following vectors represent

TABLE 1. Comparison of various virtual inertia emulation techniques based on critical factors.

Topology	Ref	Model	[a]Instability due to frequency derivative	Source behaviour	OC protection	PLL	Type of Instability
Synchronverter	[13]	SM	No	VS	No	Only for initial synchronization	Numerical instability
Modified Synchronverter	[19]	SM	No	VS	No	Self- synchronization	Numerical instability
ISE Lab topology	[11]	Swing equation	No	VS	No	Only for initial synchronization	Instability due to oscillations in power
VSG	[12]	Power-frequency relationship	Yes	CS	Yes	Mandatory	PLL instability
VISMA	[8], [9]	SM	Yes	CS	No	Only for initial synchronization	Numerical instability
Droop control	[7]	Power-frequency droop	No	Depends on switching algorithm	Yes	Mandatory	Transient instability

CS- Current source VS- Voltage source PLL- Phase-locked loop OC- Over current;
[a] Frequency derivate term is affected by errors in measurement which causes instability

TABLE 2. Comparison between synchronous machine and synchronverter derived from various references.

Classification	Ref	Factor	Synchronous machine	Synchronverter
Verification	[20]	Parallel operation	✓	✓
	[21]	Low-frequency dynamics	✓	✓
	[22], [23]	Impedance response	✓	✓
	[13]	Loss of excitation	✓	×
	[24]	Damper windings	✓	⊗
Analogy	[13]	Inertia	Fixed	Variable
	[25]	Inductance	Stator inductance	Filter inductance (30 times less than SM)
	[19], [26]	Synchronization	Automatic and manual methods	PLL and virtual impedance, resistance
	[27]	Over-excitation	Synchronous condenser	STATCOM
	[28]	Swing equation	Frictional torque	Droop control
	[29]	Frequency regulation	Governor control	Inner frequency loop

✓ Verified × Yet to be verified ⊗ Reported but not fully investigated

the stator current i, stator field φ and the spatial displacement of the rotor angle θ.

$$\varphi = \begin{bmatrix} \varphi_a \\ \varphi_b \\ \varphi_c \end{bmatrix}; \quad i = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix};$$

$$\tilde{cos}\theta = \begin{bmatrix} cos\,\theta \\ cos\left(\theta - \frac{2\pi}{3}\right) \\ cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}; \quad \tilde{sin}\theta = \begin{bmatrix} sin\,\theta \\ sin\left(\theta - \frac{2\pi}{3}\right) \\ sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}$$

The phase voltage at the synchronverter terminals is given by the equation (1), where $L_s = L + M$ is stator inductance and R_s is stator resistance. The EMF induced e in the stator depends on the rotor field excitation i_f and its relative movement with respect to the stator magnetic field (2).

$$v = e - iR_s - L_s\frac{di}{dt} \tag{1}$$

where, $v = \begin{bmatrix} v_a & v_b & v_c \end{bmatrix}^T$; $e = \begin{bmatrix} e_a & e_b & e_c \end{bmatrix}^T$.

$$e = M_f i_f \dot{\theta} \tilde{sin}\,\theta - M_f \frac{di_f}{dt} \tilde{cos}\theta \tag{2}$$

$$\frac{d\omega}{dt} = \frac{1}{J}\left(T_m - T_e - D_f\omega\right) \tag{3}$$

$$T_e = M_f i_f \left\langle i, \tilde{sin}\,\theta \right\rangle \tag{4}$$

$$P = M_f i_f \dot{\theta} \left\langle i, \tilde{sin}\,\theta \right\rangle \tag{5}$$

$$Q = -M_f i_f \dot{\theta} \left\langle i, \tilde{cos}\,\theta \right\rangle \tag{6}$$

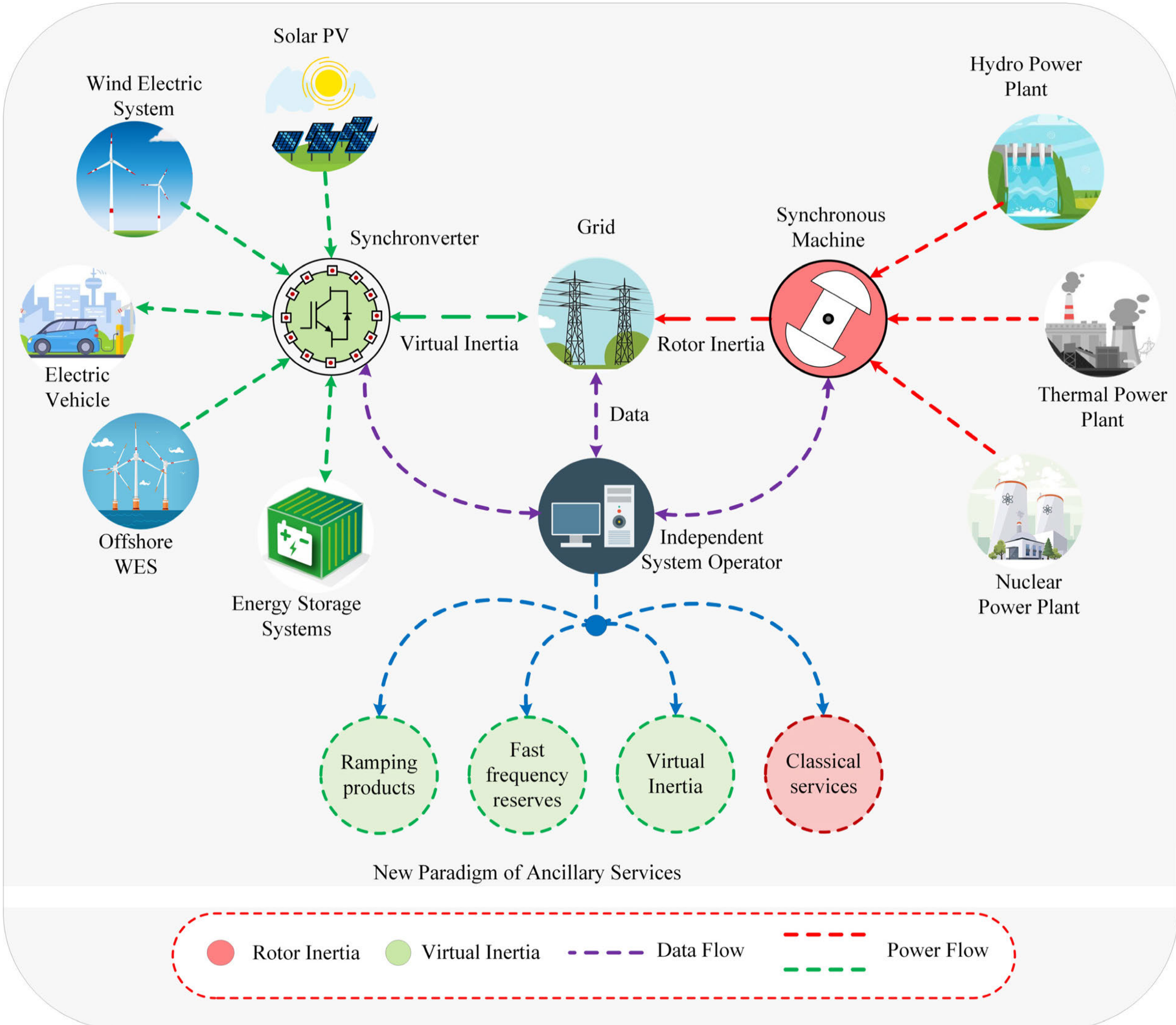

FIGURE 2. **The future power system with equal dominance of synchronverters and the potential ancillary services.**

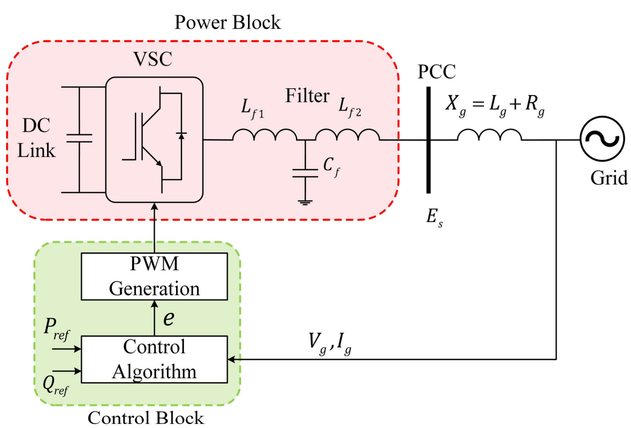

FIGURE 3. **Building blocks of synchronverter.**

The dynamic torque balance of an electromechanical system is a function of the mechanical input torque T_m, the generated electromechanical torque T_e and the frictional coefficient D_f (3), where J is the virtual inertia. The electromechanical torque is produced as a result of interaction between the stator and rotor flux (4). The real and reactive power equations are finally derived as (5) and (6) respectively, where $\langle \cdot, \cdot \rangle$ is the Euclidean inner product on $\mathbb{R}^3$. Although the original modelling has been carried out in *abc* reference frame, the small-signal modelling in the *dq* reference frame is recommended to compare the performance of synchronverter and vector control strategies. Moreover, the modelling of synchronverter in *dq* reference frame also offers a simple approach to design and analyse the performance of the controller [30].

2) CONTROL OF SYNCHRONVERTER

To mimic the overall behaviour of SM, the empirical model has been augmented with the real power loop (RPL) and reactive power loop (RePL) (*see* Fig. 4). The power regulation control has a cascaded structure with the inner and outer loops. As a rule of thumb, the interior loops are tuned

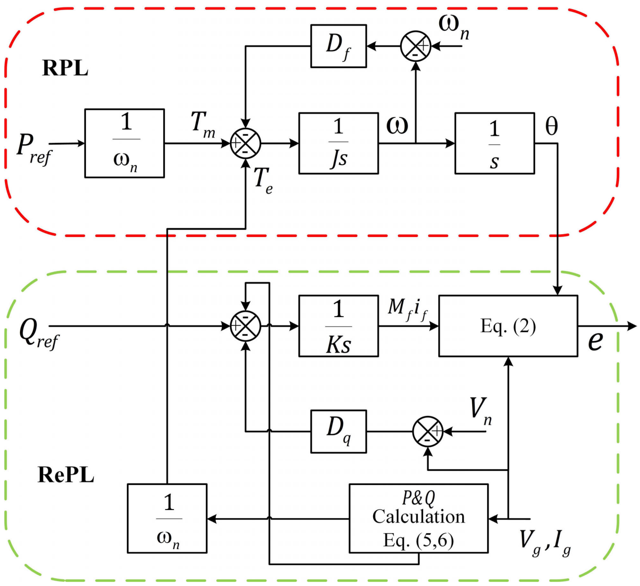

FIGURE 4. Control architecture of original synchronverter [13].

to have higher bandwidth than the outer loops, to achieve the steady-state operating stability. Moreover, the original synchronverter model has been derived by assuming a high inductive output impedance so that the relationship between $P-f$ and $Q-V$ is valid. However, the relationship is no longer valid in the low voltage networks which have high resistance [31]. The term $D_f\omega$ in (3) is analogous to the speed governor with no time lag and it has been altered to realize the $P-f$ droop (7), where ω and ω_n are synchronverter and nominal frequencies respectively [29]. Henceforth, D_f will be denoted as power droop coefficient. The mechanical torque T_m is derived from the reference power input P_{ref}. Similarly, the direct dependence of reactive power on the terminal voltage is used to realize the $Q-V$ droop (8), where D_q is the voltage droop coefficient, Q_{ref} is the reactive power reference, V_g and V_n are actual and reference voltages of grid respectively.

$$J\frac{d\omega}{dt} = T_m - T_e - D_f(\omega_n - \omega) \tag{7}$$

$$\frac{d\varphi}{dt} = \frac{1}{K}\left(\left(Q_{ref} - Q\right) - D_q\left(V_n - V_g\right)\right) \tag{8}$$

where, $\varphi = M_f i_f$.

3) SMALL-SIGNAL MODELLING

Small-signal model is essential to analyse the stability of the system under various scenarios. The non-linear equations are linearized around an initial operating point for a small change in the input. The discussion presented in this section forms the basis for stability assessment techniques presented in section IV. By linearizing, the swing equation (7) and the reactive power loop equation (8) yields equations (9) and (10) respectively. The small-signal model of synchronverter can be represented either as a transfer function or as a state-space model. However, the state-space modelling has been extensively used and it is presented after linearizing the equations around a quiescent point (12), (13) [28].

$$\frac{d\Delta\omega}{dt} = \frac{1}{J}\left[\Delta T_m - \frac{\Delta P}{\omega} - D_f\Delta\omega\right] \tag{9}$$

$$\frac{d\Delta\varphi}{dt} = \frac{1}{K}\left[\Delta Q_{ref} - \Delta Q - D_q\Delta V_g\right] \tag{10}$$

$$\frac{d\Delta\theta}{dt} = \Delta\omega \tag{11}$$

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{12}$$

$$\Delta y = C\Delta x + D\Delta u \tag{13}$$

$$\text{where, } \Delta x = \begin{bmatrix}\Delta\omega\\ \Delta\varphi\\ \Delta\theta\end{bmatrix};\ \Delta u = \begin{bmatrix}\Delta P_{ref}\\ \Delta P\\ \Delta Q_{ref}\\ \Delta Q\\ \Delta V_g\end{bmatrix};\ \Delta y = \begin{bmatrix}\Delta e\\ \Delta\theta\end{bmatrix}$$

$$\Delta e = M_f i_{f0}\Delta\omega + \Delta M_f i_f \Delta\omega_0 \tag{14}$$

A small change in induced EMF is obtained by linearizing the product of φ and ω around the initial operating point i_{f0} and ω_0. Thus, the state-space matrices corresponding to equation (14) are given below.

$$A = \begin{bmatrix}0 & 0 & 0\\ 0 & -\frac{D_f}{J} & 0\\ 0 & 1 & 0\end{bmatrix};\quad B = \begin{bmatrix}0 & 0 & \frac{1}{K} & -\frac{1}{K} & \frac{D_q}{K}\\ \frac{1}{J\omega_0} & -\frac{1}{J\omega_0} & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0\end{bmatrix};$$

$$C = x\begin{bmatrix}\omega_0 & M_f i_{f0} & 0\\ 0 & 0 & 1\end{bmatrix};\quad D = [0]_{2\times 5}$$

It is evident from the state-space matrices A and B that the control parameters D_f, D_q, K, J can be properly tuned to achieve the desired performance of synchronverter. The state-space matrices have been attained for the original synchronverter strategy without any modifications. Meanwhile, the modification on control loops increases the dimension of the state-space matrices which indicates the increase in control flexibility. A state-space model of synchronverter has been obtained by linearizing the real and reactive power equations around the quiescent operating point of synchronverter. In grid connected operation, the state-space matrices can be treated as constant, since the operating point remains unchanged (*see* Fig. 5) [32].

Since, the synchronverter is a higher-order multi-input and multi-output (MIMO) system with multiple control loops. The control parameters estimated by assuming complete decoupling between the loops might result in errors. Moreover, the linearized state-space models cannot be extended for an interconnected system. On the contrary, the component connection method (CCM) allows modular integration of the state-space models of parallel operated synchronverter using the interconnection matrices [20]. Furthermore, under system unbalance, it is not feasible to attain a fixed equilibrium through the transformation from *abc* to the *dq* reference frame. Since, the state variables are vulnerable to second

TABLE 3. Comparison of various augmentation to synchronverter to improve the dynamic response.

Augmented branch	Reference	Topology 3Φ/1Φ	Validation	Advantages	Recommendations
Damping correction loop	[29]	3Φ	PSCAD/EMTDC	• Damping correction for enhanced transient response. • Introduced torque derivative term acts only during transients.	• Coordinated tuning approach for damping and droop coefficients can improve the response of the system.
Damping correction loop	[37]	1Φ	PSCAD/EMTDC	• Power calculation using single-phase PQ theory. • Decoupled power droop and damping coefficient	• The frequency variation has to be estimated accurately to switch the droop control loop.
Fuzzy logic control	[38]	3Φ	MATLAB-Simulink	• Virtual inertia is optimized by fuzzy logic. • Fuzzy-inputs: Angular speed deviation and gradient. • Damping coefficient remains un-altered.	• A careful derivation of membership functions can accurately optimize virtual inertia.
Feedforward compensation	[36]	3Φ	DSP-TMS320F28335	• The deterrent effects due to filter bandwidth and line reactance are addressed.	• The feedforward gains can be appropriately tuned to eliminate resonant peaks.
Hold-filter for inertia control	[39], [40]	1Φ	MATLAB-Simulink	• Inertia can be controlled through variation of the time constant of the hold-filter • Better attenuation of DLFC with the hold-filter	• The filter time constant has to be determined carefully to utilize its inertial behaviour.

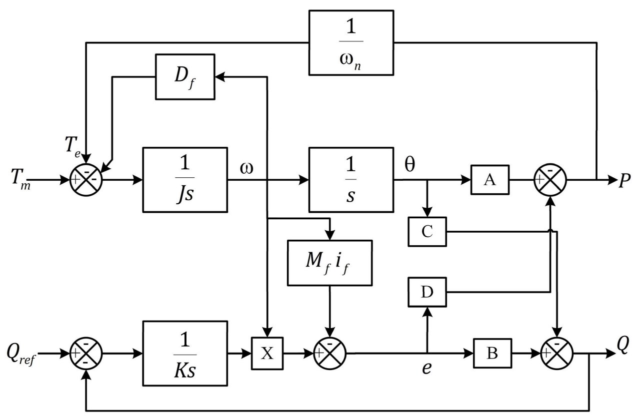

FIGURE 5. Small signal model of synchronverter with constant coefficient matrices [32].

harmonics in the *dq* reference frame. In such an instance, the dynamic phasor (DP) concept can be used to depict the attributes of quasi-periodic signals using *dc* variables [33]. A DP model of synchronverter with control and power parts has been developed to incorporate the potential system unbalances [34]. It is worth noting that, the CCM and DP methods could serve as a better alternative to the conventional approach for large interconnected systems which are prone to unbalance.

III. MODIFICATIONS TO ORIGINAL SYNCHRONVERTER

The original synchronverter topology has some inherent shortcomings like coupled droop and damping control, steady-state power deviation, the necessity of PLL for initial synchronization and absence of inherent current control. Furthermore, the assumptions like a pure inductive line impedance and a small difference in load angle between the voltages of synchronverter and grid, do not suit all the system. Thus, the original synchronverter has faced various alterations in the due course and they are reviewed in this section (*refer to* Table 3).

A. AUGMENTED CONTROL LOOPS

The power droop coefficient is determined by the power change required by the grid code and cannot be changed locally. The dependency of power deviation on the control parameters and the nominal frequency ω_n is given by equation (15). Hence, the dynamic response of original synchronverter cannot be adjusted independently without altering the steady-state droop characteristics. A simple technique to improve the dynamic response of any system is to add a derivate term to act only during the transients [35]. So, a damping correction loop has been added to the RPL with the torque derivate (*see* Fig. 6) [29]. The introduction of the damping correction loop decouples the droop and damping coefficients and offers additional flexibility.

$$\frac{\Delta P}{\Delta \omega} = -D_f \omega_n \tag{15}$$

The uncertainty between the actual and practical values of RPL bandwidth ω_f and the line reactance leads to a decrease in damping ratio and an increase in oscillation. To alleviate these issues, feedforward loops with gains, H_p and H_q have been added to the RPL and RePL respectively. The inclusion

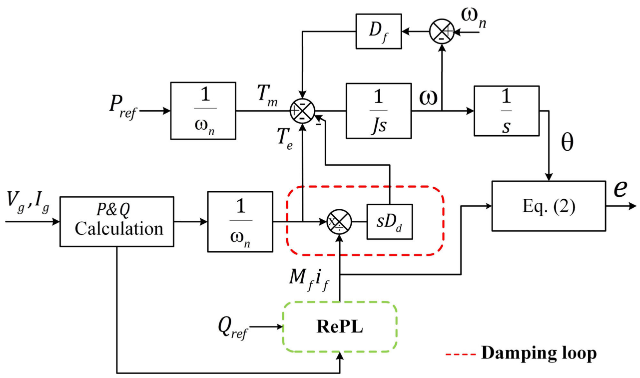

FIGURE 6. Augmentation of damping correction loop to decouple the power droop and damping coefficients [29].

of feedforward gains reduces the order of the system and offers an additional degree of freedom (16), (17), where K is the gain of field excitation loop. The gains, H_p and H_q, can be tuned to eliminate the resonant peaks and improve the dynamic response [36].

$$H_p = \frac{1}{D_f \omega_f} \tag{16}$$

$$H_q = \frac{1}{K \omega_f} \tag{17}$$

The frequency and voltage excursion caused by the non-linear characteristics of synchronverter requires additional control to maintain stability. One of the simplest solutions is to include a saturation block after the integrator in both the RPL and RePL. However, the inclusion of saturator deters the stability of the system and also causes integrator wind-up [41]. To ensure the stability limits of voltage, a bounded integral controller has been employed to limit the field current excitation [42]. However, a grid with low short circuit ratio is prone to frequency excursions, so the bounded integral controller has been extended to the frequency loop at a later stage [43]. The original frequency and field excitation loops with an integrator and the parameters virtual inertia J and gain K have been replaced with the equations derived from the bounded integrator. However, the proposed control is limited by complex computations as opposed to the simple control of original synchronverter.

The absence of inherent current control in synchronverter could damage the power converter during voltage sag in the grid. So, a current-controlled variation of synchronverter has been proposed with an internal current controller [44]. The reference current has been indirectly derived by inverting the voltage equation of synchronverter in the *dq* reference frame. Moreover, the loss of synchronism due to current saturation has been prevented by maintaining a constant difference between the angles of synchronverter and grid.

B. POWER DECOUPLING STRATEGIES

The frequency and voltage regulation mechanism of the original synchronverter has been derived by assuming purely inductive line impedance. However, in a weak grid, the line impedance has a considerable resistance R_g which results in cross-coupling between $P - V$ and $Q - \delta$ as given by equations (18) and (19) respectively [45]. Where, δ is the power angle, E_s and V_g are terminal voltages of synchronverter and grid respectively. This cross-coupling can be removed by making the line impedance inductive through an increase in the filter inductance. Nonetheless, the increase in the size of the filter inductance increases the cost of the system. Thus, a fictitious voltage drop across a virtual inductance L_v has been deducted from the induced EMF of the synchronverter. The new voltage reference is obtained through a low pass filter (LPF) with the time constant T_c (20) [46].

$$P = \frac{3E_s\left(E_s - V_g\right)}{R_g} \tag{18}$$

$$Q = \frac{-3E_sV_g}{R_g}\delta \tag{19}$$

$$E_s^* = E_s - \frac{sL_vI_g}{1 + sT_c} \tag{20}$$

Another important assumption which has been made during the design of the original synchronverter is the small power angle difference between the induced EMF and the grid voltage. However, there is a cross-coupling between $P - V$ and $Q - \delta$ at large values of power angle δ as given by equations (21) and (22) respectively, where X_g is the grid reactance. To eliminate the cross-coupling, a current feedback strategy with a dynamic current component corresponding to the coupling power values has been proposed [47].

$$\Delta P = \frac{\partial P}{\partial \delta}\Delta\delta + \frac{\partial P}{\partial V_g}\Delta V_g = 3\frac{E_sV_g}{X_g}\cos\delta + 3\frac{E_s}{X_g}\sin\delta\Delta V_g \tag{21}$$

$$\begin{aligned}\Delta Q &= \frac{\partial Q}{\partial V_g}\Delta V_g + \frac{\partial Q}{\partial \delta}\Delta\delta \\ &= 3\left(\frac{E_s}{X_g}\cos\delta - \frac{2V_g}{X_g}\right)\Delta V_g - 3\frac{E_sV_g}{X_g}\sin\delta\Delta\delta\end{aligned} \tag{22}$$

The fundamental concept of inertia emulation techniques relies on different forms of swing equation which governs the electromechanical systems. The dependence of real power on the power angle δ contributes to the non-linear attribute of the synchronverter. Thus a linear swing equation based on δ has been proposed to directly control the power angle (23) [48]. Where R_c is the ROCOF constant with the dimension s^{-2}, D_δ is the $P - \delta$ droop constant, δ and δ^* are the actual and reference power angles.

$$\frac{d^2\delta}{dt^2} = R_c\left(\delta^* - \delta - D_\delta\left(\omega - \omega_n\right)\right) \tag{23}$$

C. SELF-SYNCHRONIZATION

The synchronverter has inherent self-synchronization property similar to SM, however, the grid angle has to be furnished for initial synchronization using PLL. The PLL based synchronization suffers from various drawbacks like tuning complexity, compromise on dynamic performance

TABLE 4. Analysis of different self-synchronization strategies.

Augmented branch	Reference	Topology 3Φ/1Φ	Validation	Advantages	Limitations
Virtual impedance	[19]	3Φ	Real-time experiment	• Value of virtual inductance and resistance is chosen less than actual values.	• Sluggish response due to inductance. • The additional virtual inductance and resistance increase the complexity of parameter tuning.
Virtual resistance	[26]	3Φ	PSCAD/EMTDC	• Faster synchronization and minimum current peak when compared to the virtual impedance	• Complex virtual power computation process which increases the computation time.
PI controller	[53]	1 Φ	Real-time experiment using DSP-TMS320F28335	• Auxiliary synchronization loop is switched during reconnection. • PI controller forces the phase angle error to zero.	• Switching operation of the auxiliary loop doesn't guarantee reliable operation.

and stability margin of the system [49]. To address these issues, numerous strategies have been proposed for self-synchronization of synchronverter without employing a PLL (*refer to* Table 4). The self-synchronization is a bi-folded process, firstly, the frequency and voltage droop controls are phased out and then the real and reactive power injection is forced to zero.

The first self-synchronization strategy has been proposed by the developers of the original synchronverter [13]. A virtual impedance with inductance L_v and resistance R_v has been used to obtain the virtual current i_v for initial synchronization as per equation (24) (*see* Fig. 7). The synchronization process is successful once the induced EMF e matches with the grid voltage V_g. In addition to that, a PI controller has been augmented with the frequency control loop to generate the incremental phase angle for eliminating the steady-state error in torque [19].

$$i_v = \frac{1}{sL_v + R_v}\left(e - V_g\right) \tag{24}$$

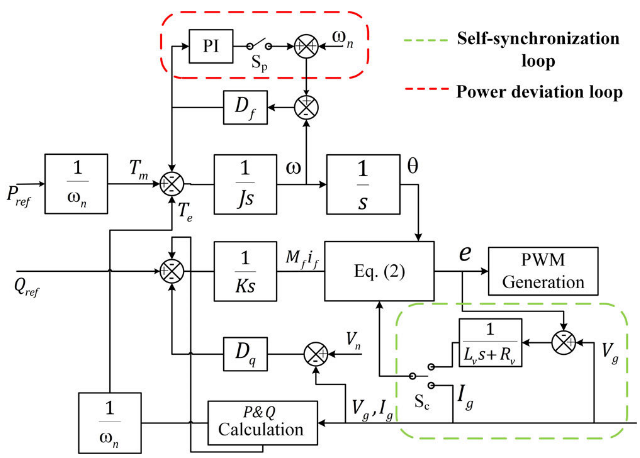

FIGURE 7. Original synchronverter with self-synchronization using virtual impedance [19].

The inclusion of a virtual impedance branch offers a sluggish synchronization process and it requires two parameters to be tuned properly for stable operation. So, a virtual resistance branch has been used for self-synchronization of synchronverter by eliminating the dynamics of the inductance [26]. Since the synchronverter has been designed by assuming inductive output impedance, the real and reactive power has to be computed virtually. So, a coordinate transformation technique with rotational matrices has been used for this purpose. Furthermore, it has been found that an increase in the power droop coefficient D_f accelerates the phase angle synchronization and a decrease in the value of K results in faster voltage magnitude synchronization. Although the virtual resistance method has a faster synchronization process, the virtual impedance method has been predominantly used for self-synchronization due to the complex power computations of the former.

A sinusoid locked loop (SLL) is an alternative to PLL which provides additional magnitude information of a periodic signal. The floating operation of SM incorporates the property of an SLL with no power exchange with the grid. Inclined by this, an SLL has been used to force the real and reactive power exchange to zero [50]. The proposed strategy has been proven to have lower frequency fluctuations and voltage harmonics when compared with SOGI-PLL [51] and sinusoid tracking algorithm [52].

D. SINGLE-PHASE SYNCHRONVERTER

The increasing trend of small DG systems necessitates a novel control for single-phase power converters. Hence, the original synchronverter has been adopted to single-phase systems with appropriate modifications. The modelling of single-phase synchronverter remains the same as the original synchronverter except for a few modifications.

1) POWER COMPUTATION

The conventional strategies of single-phase converter with the nested voltage and current loops do not require average power calculation. However, the synchronverter control demands the average power value to control the power injection. The instantaneous active (25) and reactive power (26) of a single-phase system has a double line frequency component, unlike the three-phase systems [54].

$$p(t) = \frac{1}{2} V_g I_g cos(\delta) \, sin(2\omega_n t) \tag{25}$$

$$q(t) = \frac{1}{2} V_g I_g sin(\delta) \, [1\text{-cos}(2\omega_n t)] \tag{26}$$

So, significant contributions have been made to remove the double line frequency components (DLFC) in real and reactive power. A simple strategy is to employ an appropriately tuned low pass filter (LPF) to effectively remove the DLFC [53]. The small-signal model of real power loop with LPF has been derived by considering and the time constants of frequency τ_f and power loop, τ_p (*see* Fig. 8). It is clear that the dynamic response of RPL is directly affected by the time constants τ_p and T_c, when $\tau_f \ll \tau_p$. The transfer function of first-order LPF with the time constant, T_c is given by equation (27) such that $\tau_f \ll T_c$.

$$G(s) = \frac{1}{1 + sT_c} \tag{27}$$

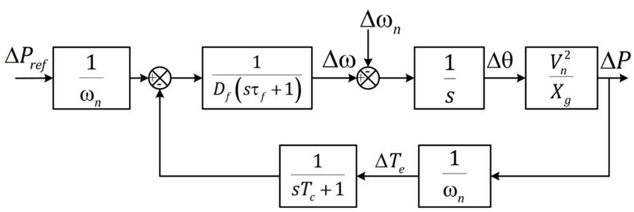

FIGURE 8. The transfer function of real power loop with a low pass filter [53].

The effect of τ_f can be neglected to reduce the order of RPL, as it does not contribute to dominant modes of the system. It is evident from the equation (28) that the damping ratio ζ depends on the ratio between τ_p and T_c. The filter time constant for a 50 Hz system should be chosen such that the cross over frequency is utmost 10% of the second harmonic [53]. However, the stable operating region is bounded by the upper and lower limits of τ_p and T_c (29) [55].

$$\zeta = \frac{1}{2}\sqrt{\frac{\tau_p}{T_c}} \tag{28}$$

$$T_c = (0.39 \sim 1.56)\, \tau_p \quad \forall\, T_c \geq 0.01 \tag{29}$$

The first-order hold filter (HF) (30) can be approximated as a first-order LPF through Taylor series expansion (31). However, HF offers better attenuation of DLFC over a wide range of time constants than LPF. Besides using it to attenuate DLFC, the effect of the filter time constant on the dynamic response has been utilized to provide additional freedom of control [56]. The effective inertia of the system has been increased by increasing the filter time constant, T_h. On contrary to the small bounded operation region of LPF, the effective inertia can be varied over a wide range to achieve the desired dynamic response [39].

$$F(s) = \frac{1 - e^{-T_h s}}{T_h s} \tag{30}$$

$$e^{-T_h s} \approx \frac{1}{1 + T_h s} \tag{31}$$

Apart from the filtration based techniques, the single-phase PQ theory has been used to calculate the average single-phase power [54]. Inspired by the Park's transformation, the single-phase coordinate transformation has been achieved through orthogonal signal generation technique with 90° spatial separations between voltage and current [51]. A second-order generalized integrator (SOGI) has been used to transform the single-phase current and voltage to the stationary reference frame ($\alpha\beta$) [37].

The use of the RMS value of current and voltage has been proposed to compute the single-phase real and reactive power [57]. However, the true RMS value can only be computed for a pure sinusoidal voltage and current. The presence of harmonics induces an error in the average power computation. Among the methods used to compute the single-phase power, the method based on hold filter offers an advantage of indirectly controlling the inertia of the system over the other methods.

2) MODIFIED SINGLE-PHASE SYNCHRONVERTERS

Inspired by the modifications introduced to the original synchronverter, the performance of single-phase synchronverter has been enhanced by augmenting it with various control loops. However, an effort has been made for utilizing the three-phase equations of original synchronverter to realize the single-phase synchronverter without considerable modifications. The three-phase currents have been derived from the single-phase current through a current emulation strategy (*see* Fig. 9). A PLL has been used to derive the phase and frequency of the line current whose magnitude $|u|$ has been estimated to generate three-phase currents with 120o space separation [58].

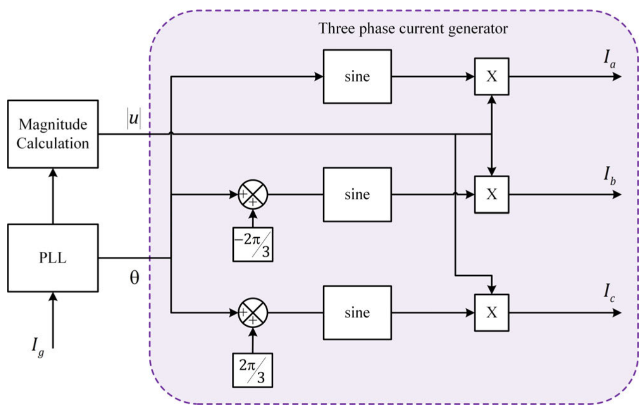

FIGURE 9. Three-phase current emulator for single-phase synchronverter [58].

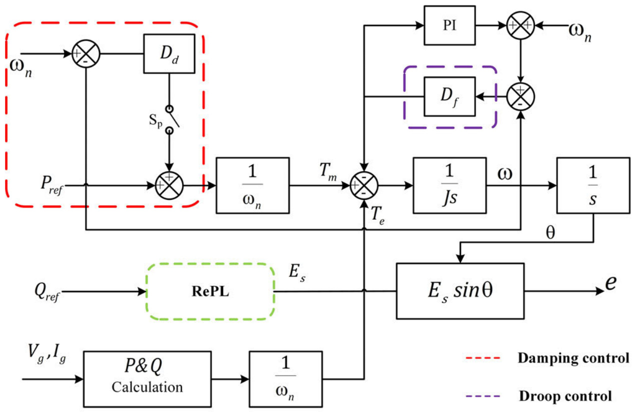

FIGURE 10. Decoupled damping and droop coefficient for single-phase synchronverter proposed in [59].

As discussed earlier, the grid code constraint on power droop coefficient compromises the control flexibility of synchronverter. So, the damping and droop functions have been decoupled to enhance control flexibility and eliminate steady-state deviation. The damping action from inner frequency loop has been moved to the outer active power loop for independent tuning. Meanwhile, the steady-state power deviation has been nullified through a PI controller (*see* Fig. 10) [59], [60].

The three-phase synchronverter model has been predominantly adopted to meet the specific requirement of single-phase systems. However, a few different configurations of synchronverter have been proposed without compromising on the dynamic characteristics of the original synchronverter. One such strategy has used a PI controller to realize the reactive power regulation and retains the real power loop (*see* Fig. 11) [57]. The angle θ derived from RPL has been used to generate a unit template with sinusoidal variations. The PI controller in the RePL has been used to control the reactive power injection.

However, the proposed synchronverter operates as a current source which contradicts the behaviour of original synchronverter. Similarly, the RPL has been retained and the RePL has been modified with a PI controller for voltage regulation [59]. The single-phase power values have been derived through orthogonal signal generation using a SOGI. In both the works the effect of field excitation has been neglected which is an integral part of an SM. A comprehensive review of control modifications made to achieve a certain objective is presented in Table 5.

IV. PARAMETER TUNING AND STABILITY ASSESSMENT OF SYNCHRONVERTER

The small-signal model presented in section II.A.3 has brought out the control variables of synchronverter which have to be tuned to achieve a stable response. So, the parameter tuning methods are reviewed, followed by the stability assessment techniques in this section.

A. PARAMETER TUNING METHODS

In the recent past, the parameters of synchronverter and VSG have been tuned using both offline and online methods. The offline techniques employ small-signal analysis [69], [70] and mathematical relationships [13] to determine the parameters before taking the system online. The online techniques alter the parameters in real-time to achieve the desired behaviour [71], [72]. However, the main drawback of the online tuning approach is the additional computational burden.

1) EMPIRICAL RELATIONSHIP

The original synchronverter has been tuned using the empirical relationship between the system variables and the control parameters as given by the following equations (32)-(34) [13]. Where τ_f and τ_v are the time constants of frequency and voltage loops respectively. The coefficients, D_f and D_q, have been determined by the required torque change ΔT and reactive power change ΔQ for frequency and voltage regulation of the system respectively. Although this technique offered a simple approach to tune

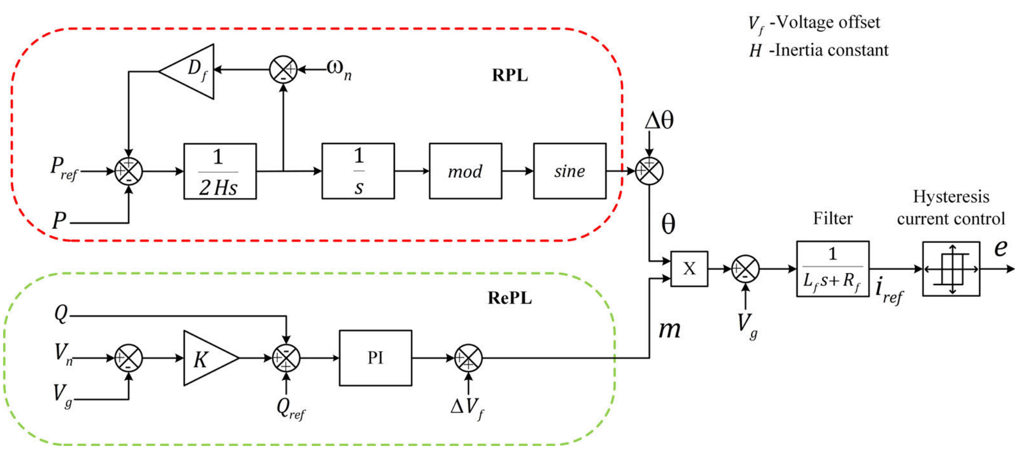

FIGURE 11. Model of single-phase synchronverter proposed for integration of solar rooftop plant [57].

TABLE 5. **Review of synchronverter control adaptation to achieve various objectives.**

Control objective	Ref	Topology 3 Φ/1Φ	Validation of control strategy	Control adaptation	Remarks
Stability enhancement	[25], [61]	3Φ	MATLAB-Simulink & Real-time experiment	Emulation of virtual inductance and capacitor	• Virtual increase in filter inductance for better stability. • Anti-windup mechanism for field current control. • Virtual capacitor for DC component filtering.
	[42], [62]	3Φ	OPAL-RT real-time simulation	Bounded integral control	• Bounded integral controller for frequency and field current control. • Saturators are eliminated for better stability.
	[48]	3Φ	MATLAB-Simulink	δ-based swing equation	• Linear control is possible through δ-based swing equation.
	[24]	3Φ	MATLAB-Simulink	Damper windings	• Damper windings are included to dampen the hunting phenomena. • Effect of damper windings neglected for parameter tuning.
Fault current limitation	[63]	3Φ	PSCAD/EMTDC, HIL	Hysteresis current controller	• Hysteresis current controller for fault current limitation. • Only validated for symmetrical faults.
	[44]	3Φ	Real-time experiment	Inner current control	• Harmonic voltages are eliminated by the current control loop. • Current saturation is avoided through load angle control.
	[64]	3Φ	PSCAD/EMTDC	Active voltage feedback	• Switchable loops are used for current and voltage control.
	[59], [60]	1 Φ	Real-time experiment	Resonant current control	• Current reference is switched between a fixed and the actual value
Power sharing	[65]	3Φ	MATLAB-Simulink	T-S fuzzy controller	• Synchronverter applied in charging stations of EV. • Power reference derived through fuzzy logic control • Deep discharge of EV batteries is avoided by dynamic droop control
	[66]	3Φ	OPAL-RT real-time simulation	Consensus-based droop control	• Two-phase consensus-based droop control for power sharing between synchronverters. • RePL is replaced by $Q - V$ droop.
Output power decoupling	[46]	3Φ	MATLAB-Simulink	Voltage-tracker with nested voltage and current loop	• Output power decoupling through virtual impedance variation. • Power loss in virtual impedance is compensated through an additional term.
	[47]	3Φ	MATLAB-Simulink	Current feedback control	• Output power decoupling during the large variation in δ. • Resonance at the fundamental frequency is eliminated.
Harmonic current sharing	[67]	3Φ	Real-time experiment	Finite-gain repetitive controller	• Harmonic current sharing though the variation of virtual output impedance. • Controller gain is adjusted for better Harmonic selectivity.
Frequency and voltage control	[68]	3Φ	MATLAB-Simulink and Hardware in loop simulation using OPAL-RT	Normalized droop control	• Normalized droop control for frequency control in AC-grid and voltage control in DC-grid of hybrid AC-DC microgrid.

the parameters, it compromises the accuracy of placement of dominant poles of the system.

$$D_f = -\frac{\Delta T}{\Delta \omega} \tag{32}$$

$$J = D_f \tau_f \tag{33}$$

$$D_q = -\frac{\Delta Q}{\Delta V_g} \tag{34}$$

$K \approx D_q \tau_v \omega_n$; when $\Delta\omega$ is very small.

An iterative procedure has been proposed to continuously optimize the parameters based on the movement of dominant poles in the S plane [29]. Further investigation has revealed that the parameter D_d of the damping correction loop directly affects the dominant poles of RPL. In such a case, the iterative procedure may not obtain appropriate values for accurate placement of dominant poles. This limitation has been addressed through a sequential process developed for the third-order linearized model of synchronverter with the damping correction loop. Firstly, a criterion has been developed to predict the effect of variation of D_d on the movement of dominant poles of the system. Subsequently, an empirical formula to directly compute the values J and D_d has been derived using Vieta's formula [73] to place the complex-conjugate roots of synchronverter [74].

The introduction of self-synchronization mechanism into the original synchronverter has further increased the complexity of the tuning procedure with the additional parameters to be tuned. The values of L_v and R_v can be chosen less than the actual values of synchronverter [19]. Nonetheless, the small values of L_v lead to large current transients and a much smaller value of L_v and R_v leads to sustained oscillations in the frequency. Moreover, the ratio R_v/L_v should also meet the cut-off frequency requirement of the filter used to attenuate the harmonics in voltage feedback. Similarly, the voltage regulation loop with a gain K_v in parallel to RePL should be tuned in tandem with the gain K such that the voltage loop acts faster than the outer loop (35) [27].

$$K_v = \frac{D_q}{K} \tag{35}$$

2) ANALYTICAL TECHNIQUES

The method of specific residues for tuning of parameters is based on the sensitivity of poles to the control variables of the system. The sensitivity of poles to the i^{th} variable p of the k^{th} controller $K_{ik}(s, p)$ in a closed-loop system with the linearized transfer function $H_{ik}(s)$ is given by equation (36), where $\Re$ is the residue of $H_{ik}(s)$ at pole λ.

$$\frac{\partial \lambda}{\partial p} = \Re_{\lambda} \frac{\partial K_{ik}(s, p)}{\partial p} \tag{36}$$

The residues of the transfer function determine the participation factor of each pole corresponding to a particular dynamics of the system. An analytical tuning approach based on specific residues has been presented to derive the synchronverter parameters considering the less dampened dominating modes of oscillations [75], [76]. The variation of control parameter K_m shifts the pole from its initial point λ_n^0 to a new point λ_n (37), where n and m are iterative variables. Since several poles contribute to a single dynamics of the system, a coordinated tuning approach has been used to obtain the control parameters. The coordinated tuning has been converted to an optimization problem and the *argmin* function has been used to determine the pole location with respect to the desired pole location λ_n^* (38) [82].

$$\lambda_n = \lambda_n^0 + \sum \Re_{nm} K_m \tag{37}$$

$$K_m = argmin \sum_n \left\| \lambda_n^* - \lambda_n \right\|^2 \tag{38}$$

A fuzzy logic approach has been proposed to optimize the virtual inertia J to achieve a better trade-off between response rate and the damping ratio of the system [38]. The fuzzy rule base has been formulated using the angular speed deviation and the angular speed gradient as inputs. The search plane for the virtual inertia has been defined based on the required system response for the second-order characteristic equation of synchronverter. A larger inertia value has been used to suppress the oscillation, whereas a smaller value has been used for faster frequency restoration.

The presence of LPF in the control loop of synchronverter increases the order of the system which can directly alter the dominant pole location on the S plane. It is worth mentioning that the effect of low pass filter in the RPL and RePL have been neglected in all the works except [55], [74]. Furthermore, the use of direct empirical relationships offers an easier approach to tune the control parameters without high computational efforts. However, the analytical approaches allow more accurate placement of dominant poles on the S plane which improves the system dynamics.

B. TIME-DOMAIN ANALYSIS

The eigenvalue analysis of state-space models has been widely used to analyse the stability of traditional power system, which were adopted to power electronics domain at a later stage [83]. The stability of the system is assessed by tracing the loci of eigenvalues in the S plane with the variation of the state variables. The participation factor of each mode determines the dominant modes which contribute to system oscillations [84]. The eigenvalue analysis has been used to assess the effect of grid impedance variation on the stability of synchronverter [85]. The complex conjugate eigenvalues traced the loci parallel to the imaginary axis with the increase in grid inductance and became real after a critical value. The trajectory of eigenvalue indicates the increase in stability with the corresponding increase in grid inductance. However, the increase in grid resistance can force the eigenvalues to enter the right half of the S plane leading to instability.

Similarly, the effect of output filter resistance on the stability of synchronverter has been analysed through eigenvalue analysis [86]. The value of critical resistance has been obtained at the point of intersection of eigenvalue loci and the imaginary axis. However, a further increase beyond the critical resistance can move the eigenvalues to the left half of the S plane. Besides the state-space model, the transient stability of synchronverter dominated microgrid under unbalanced conditions has been investigated through eigenvalue analysis using a DP model [34]. It has been realized that the control parameters, J and K of synchronverter has a high impact on the low-frequency dominant modes.

TABLE 6. Critical analysis of stability assessment method.

Category	Methods	Stability criteria	Computation intensity	Advantages	Limitations	Recommendations
Time-domain	Eigenvalue analysis [77]	Tracing the loci of eigenvalues on the S plane	High	• It is a simple approach to predict the global stability of the system. • Dynamic modes can be identified. • The participation factors of every state variable can be determined.	• It does not offer modularity and has a low level of scalability. • The formation of state-space matrices and repeated estimation of eigenvalue increases the processing time. • Not suitable for MIMO systems.	It is the most popular stability assessment technique due to its simplicity. Hence, it can be applied to all the systems without any limitations.
	Bifurcation theory [78], [79]	Identification of bifurcation points	Low	• The use of test functions to find the bifurcation points reduces the computation time. • Bifurcation graphs visually present the variation of stability margin.	Conventional methods used to detect saddle-node bifurcation are time-consuming due to its bi-fold process of solving and tracing the equilibrium points.	It is best suited to analyse the stability of synchronverter based system under parameter variation.
Frequency domain	Structured singular value analysis [21], [28], [80]	μ- factor is used instead of phase and gain margin	High	• It incorporates uncertainties in the system as opposed to conventional eigenvalue and impedance based methods. • It can handle multiple parameter uncertainty of the power system. • It can track uncertainties under the non-linear behaviour of the system.	• Exact calculation of μ-factor for large systems are computationally intensive. • The perturbation pattern does not have a well-defined mechanism. • Complex mathematical attributes increase computation time. • The physical interpretation of the algorithm is still unclear for its application in power systems.	It is a better choice for MIMO systems like synchronverter which are prone to various uncertainties.
	Impedance based methods [22], [23], [77]	Generalized stability criterion	Low	• It allows generic modelling with an ability to derive impedance profiles using frequency scanning method. • It facilitates lower computation demand with the use of nodal admittance matrix, thus, offering better scalability.	• The existence of poles in the right half of the S plane may result in an inaccurate assessment. • It cannot assess the global stability of the system which demands a separate assessment of all subsystems.	It can be applied to assess the stability of large interconnected systems.
Direct methods	Potential energy boundary surface [56], [81]	Transient energy function	Moderate	• It provides a quantitative value for the degree of stability of the system. • It can compute the sensitiveness of stability margin to system parameters. • It is computationally less intensive than time-domain methods.	• It does not provide time response of the system state variables. • The construction of transient energy function if a tedious process. • The computation of unstable equilibrium points increases the computational intensity.	• It can be used to analyse the relative stability of different systems for comparing its stability. • It can also be used to directly determine the stability margin of the system.

The eigenvalues have moved towards the origin and remained in the left half of S plane with the increase of J and K. The loci of eigenvalues indicate a poor dynamic response with under-damped oscillations. However, the decrease in droop coefficients, D_f and D_q, can push the eigenvalues to the right half of the S plane causing instability.

In addition to eigenvalue analysis, the bifurcation theory has also been used to determine the dynamic stability of microgrid with synchronverter [78]. The increase of D_f has forced the eigenvalues towards the origin but held it in the left half of S plane resulting in no bifurcation phenomena. However, a decrease in the value of D_q has resulted in Hopf bifurcation which moved the eigenvalues to the right half of S plane. Furthermore, the saddle-node bifurcation has been observed when the filter inductance has been increased, with the movement of dominant mode towards the origin [78].

C. FREQUENCY DOMAIN ANALYSIS

The impedance-based methods are one of the popular strategies for stability assessment of a closed-loop system in the frequency domain. The impedance method has been originally employed to analyse the effect of input filters of DC-DC converters [87] and it has been later adapted for AC power converters [88], [89]. Firstly, the Thevenin or Norton equivalents are used to derive the AC input and output impedances of the components in a closed-loop system. Subsequently, a generalized stability criterion is used to determine the stability of the system through the impedance ratio of the minor feedback loop.

The impedance model of the synchronverter has been analytically derived from the linearized phase voltage and current equations [22]. It has been found that the impedance characteristics of synchronverter have good agreement with the RL-circuit, similar to SM. The minimum interaction between the control loops of synchronverter is the reason behind its similarity with an RL-circuit, unlike the vector control. Furthermore, the vector controlled voltage source converters (VSC) exhibit complex impedance characteristics above and below 2 kHz. Above 2 kHz, the inductive characteristics have been exhibited. However, below 2 kHz, the vector control has multiple resonant peaks which could lead to oscillatory response and voltage instability [22], [23].

The synchronverter model is a MIMO system with uncertainties in input and output variables which requires a multivariable stability analysis technique. The nonlinearities and the parameter variation of synchronverter with frequency dependency can be better appreciated with the frequency domain analysis. The structured singular value analysis μ- Analysis) is one such technique used to assess the stability of the power system [90].

Recently, this robust analysis technique has been used to analyse the stability of synchronverter under the variation of parameters J, K and short circuit ratio (SCR) of the grid [21], [28]. The stability margin of the system has been determined using the μ - factor, since the gain and phase margins cannot be used for a MIMO system [91]. The increase in the value of J enhances the stability, however a very high value of J reduces the stability at lower frequencies. Thus, it is not necessary to have a value of J equivalent to that of SM, as it would increase the energy storage requirement at the DC link. The stability of the system increases in proportion with the increase in K and the effect becomes negligible after a certain value.

The synchronverter is more stable under high-frequency uncertainties when connected to the grid with high SCR. However, it is affected by the low-frequency uncertainties when connected to a weak grid. Simultaneously, the synchronverter offered better stability during high-frequency uncertainties under weak grid conditions which contradicts the behaviour of VSCs in a weak grid [21]. It is worth noting that the effect of SCR on stability by eigenvalue analysis had a contradictory notion with the μ- analysis.

D. DIRECT METHODS

The direct methods are the alternatives to time domain and frequency domain analysis to assess the stability of the system. The direct methods utilize the transient energy function (TEF) models to evaluate the stability of the system after a disturbance [92]. It employs a sequential process to assess the stability of the system by comparing the energy at the initial state to a critical value. The system remains stable after a disturbance if the energy at the initial state is greater than the critical energy value. Meanwhile, the system becomes unstable for the converse condition. The energy function of synchronverter given by (39), is the sum of kinetic energy contributed by the virtual rotor velocity $K(\omega)$, potential energy contributed by virtual rotor angle $W_1(\delta)$, magnetic energy stored $W_2(\delta, E_s)$ and the induced EMF $W_3(E_s)$ [66].

$$H(\omega, \delta, E_s) = K(\omega) + W_1(\delta) + W_2(\delta, E_s) + W_3(E_s) \quad (39)$$

The simplified closed-loop model for stability analysis of synchronverter is expressed by (40), where δ, E_s and $\dot{\theta}$ are state variables, J and D are positive diagonal matrices and G is the coefficient matrix. The movement of eigenvalues of the characteristic equation (41) defines the system stability. The potential energy boundary surface (PEBS) technique has been used to analyse the stability of synchronverter through the derived TEF [56]. The relative error between the eigenvalue analysis and the PEBS method is quite small which proves its feasibility for analysing the stability of synchronverter.

$$J\ddot{\theta} = -D\dot{\theta} - G\frac{\partial W(\delta, E_s)}{\partial \delta} \quad (40)$$

$$\tilde{G} = (G + G'); \quad G' = D^{-1}G \quad (41)$$

E. PARALLEL CONNECTED SYNCHRONVERTERS

In the weak power grids, the synchronization units (PLLs) of parallel-connected converters interact with each other and generate transient oscillations. Additionally, the interactions between controllers of power converters in the same area induce a negative effect on system stability. Meanwhile, the control loops of a synchronverter alter the frequency response of the equivalent grid containing parallel operating synchronverters. Thus, the increase in penetration level of DG demands a further investigation of the interaction between synchronverters in the same area.

1) EFFECT OF PARAMETER VARIATION

The μ- analysis has shown that the system with parallel operating synchronverters has a lower stability margin than the system with single synchronverter [93]. The variation of the grid and synchronverter parameter has different behaviour when there are parallel operating synchronverters nearby. As discussed earlier, the increase of SCR enhances the stability under high-frequency disturbances. However, it does not have a significant effect on the stability of the system with parallel operated synchronverters.

Besides the grid parameters, the variation of control parameters D_f and D_q also affect system stability. An increase in D_f decreases the stability margin and initiates the instability. Whereas, a decrease in D_q impedes the system stability with oscillations in the output current and voltage [78]. However, the stability margin of a system with parallel-connected synchronverters can be enhanced by increasing the size of the filter inductance. For instance, an increase in the output filter inductance by 30% increases the stability margin [20]. Moreover, the size of filter resistance should be limited as it contributes to multiple resonant peaks around the fundamental frequency. Also, a physically large filter would cause more loss and incur high cost. So, the size of the filter with inductance L_f and resistance R_f can be virtually increased. To virtually increase the filter inductance n times, $(n-1)$ fictitious voltage drop has been added to the actual induced EMF of synchronverter as per (42) (*see* Fig. 12) [25]. The corresponding increase in the filter resistance has been eliminated by including the virtual power loss into the power balance equation [25], [61].

$$E' = \frac{(n-1)\,V_g + E_s}{n} \tag{42}$$

A decision matrix is derived by analysing the movement of eigenvalues in the S plane. The effect of parameter variation on the system stability and dynamic performance is mapped by variation from lower (red) to a higher (green) value through intermediate values (yellow, orange). The subsequent blocks with the same colour indicate that the variation in parameter does not have any effect on system response beyond certain value (*see* Fig. 12).

2) HARMONIC CURRENT MITIGATION

The absence of current control in synchronverter limits its capability to mitigate the power quality problems and facilitate harmonic current sharing. The harmonic virtual impedance technique has been widely used to mitigate the power quality concerns in the microgrid with parallel operated VSCs [31]. Similarly, harmonic virtual impedance technique has been used to suppress the harmonics in parallel operated synchronverter environment [94]. An inner current controller has been proposed to limit the current under grid disturbances [95].

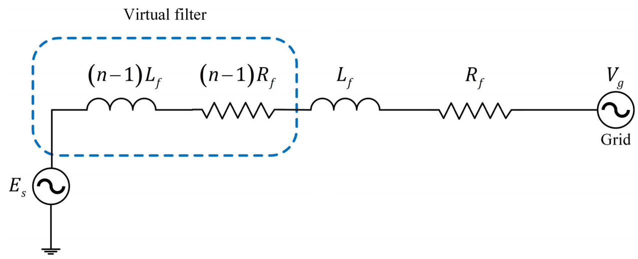

FIGURE 12. Equivalent circuit of strategy to virtually increase the filter size [25].

The current reference has been indirectly computed by inverting the steady-state voltage equation of synchronverter in the dq reference frame [44]. A discrete-time parametrization approach has been used to derive the virtual impedance for better harmonic selectivity [96]. The increase in virtual resistance can improve the harmonic tracing but compromises the stability margin [94]. Moreover, a high value of virtual resistance would degrade the harmonic current sharing among the parallel synchronverters.

V. APPLICATIONS OF SYNCHRONVERTER

The ability of synchronverter to mimic the desirable properties of an SM has led to its extensive application over other inertia emulation strategies. Besides virtual inertia emulation, various researches have been carried out to realize the benefits offered by SM in stability enhancement and oscillation damping of the power system. The applications are categorized and critically reviewed in this section.

A. POWER SYSTEM STABILITY

1) INTER-AREA OSCILLATION DAMPING

The low-frequency electromechanical oscillations in the frequency range of 0.1 Hz to 0.8 Hz are termed as inter-area oscillations [97]. Conventionally, the power system stabilizers utilize the relationship between the active power and stator EMF to dampen these oscillations. Similarly, the time constant of the frequency control loop of the synchronverter can be altered to dampen the inter-area oscillations.

In a multi-area power system, the synchronverters in each area has been controlled to generate additional viscous frictional torque to dampen the inter-area oscillations [98]. After a disturbance, the virtual rotor angles rotate against each other and the additional torque is released by the synchronverter. However, under steady-state, the frictional torque component becomes null as there is no phase difference between the angles of synchronverter. The transient stability of a two-area power system with SM is said to be enhanced with at least one synchronverter in each area [99]. However, a high bandwidth communication channel is required between the synchronverters for reliable operation.

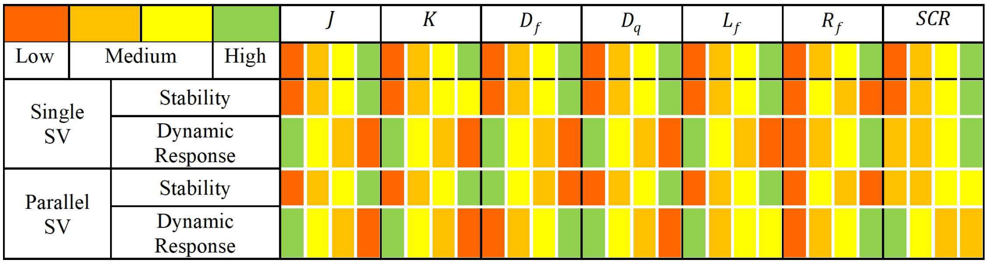

FIGURE 13. **Decision matrix for parameter tuning to achieve a trade-off between system performance and stability [20], [29], [78], [93].**

2) SEAMLESS TRANSFER

The seamless mode transfers between grid connected to islanded and vice versa should be carried out with minimum influence on the loads in the microgrid. During disconnection from the grid, the current surge is minimal as the output voltage and frequency is not affected considerably. Whereas, during reconnection with the grid, the phase angle of the grid voltage and the synchronverter voltage has to be matched for hot transfer.

So, an auxiliary control branch with a PI controller has been introduced to track the phase angle difference and force it to zero [53]. Another self-synchronization strategy has been proposed based on angular frequency compensation $\Delta\omega_{syn}$ through a PI controller (*see* Fig. 14). The grid voltage has been aligned with its direct axis component and the quadrature axis component has been forced to zero by the PI controller [100]. Nevertheless, to facilitate reconnection after a shutdown, a sequential black start procedure has been proposed for the parallel operated synchronverters in an isolated microgrid [101].

By far, the mechanisms developed for seamless transition have assumed perfect knowledge on island detection and also requires control loop reconfiguration. Recently, a synchronization technique based on the virtual torque T_{syn} and virtual flux φ_{syn} has been proposed which does not demand controller reconfiguration. The virtual flux and torque values have been obtained by introducing synchronizing gains in the control loop of synchronverter (*see* Fig. 15) [102]. On the contrary to other strategies, the PLL employed might affect system stability.

3) STABILITY ENHANCEMENT

Similar to SM, synchronverters have been used to enhance the stability of the interconnected system. An increase in the damping coefficient has resulted in an increase in critical clearing time (CCT) and hence the stability margin [56]. Meanwhile, the damping of low-frequency oscillations has enhanced the rotor angle stability. Furthermore, the voltage loop parameters determine the post-contingency equilibrium, where a very low value would cause instability. Lately, the effect of damper windings has been included in the synchronverter to alleviate the hunting phenomena after a contingency event [24]. Under steady-state, the damper

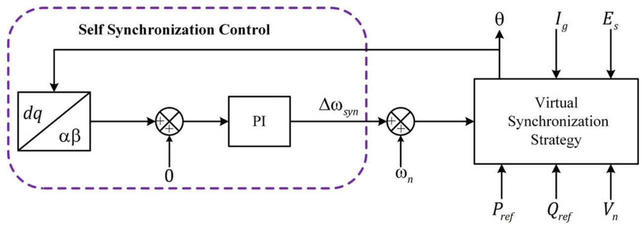

FIGURE 14. **Self-synchronization strategy based on angular frequency compensation for seamless transfer [100].**

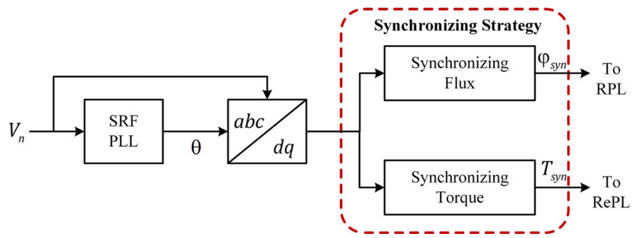

FIGURE 15. **Self-synchronization strategy based on virtual torque and flux for seamless transfer [102].**

windings have zero effect on the dynamic response of the synchronverter. However, they can reduce the oscillations and overshoot after a contingency event.

The peak fault current contribution of synchronverter can reach several times the rated current within a few milliseconds. So, a hysteresis controller has been used to limit the high transient fault current of synchronverter [63]. However, the control strategy has been validated only for the symmetrical grid faults. Unlike SM, the sequence components of the synchronverter remain equal as its output impedance remains constant after an unbalanced fault. So, a fault analysis technique based on instantaneous symmetric components has been proposed to analyse the transient stability of synchronverter under unbalanced faults [103]. The voltage-controlled synchronverters have an inherent delay to the grid faults which results in a voltage difference between the grid and synchronverter. Thus, a voltage feed-forward compensation has been added to limit the fault current and provide active power support to the grid [104]. However, the deep learning algorithm used to predict the output current demands periodic training.

TABLE 7. Comparison between synchronverter and vector control derived from various references [30], [105], [106], [112].

Factors	Synchronverter	Vector Control
Equivalent model	Voltage source	Predominantly current source
Synchronization	Self-synchronization through virtual impedance/resistance	Requires PLL
Current limiting	No inherent current limiting capacity	Inner current loop limits the current
Inertial response	Emulation of virtual inertia	No inherent virtual inertia
Stability	Numerical instability	Grid parameter variation causes instability
Power decoupling	Complete decoupling	Feedforward loops are used for decoupling

B. BACK TO BACK TOPOLOGY

The back to back (B2B) topology consists of two synchronverters decoupled by a DC link. Where one synchronverter is operated as a synchronous motor and the other synchronverter is operated as a synchronous generator. The idea to operate a PWM rectifier as a synchronous motor has been initially proposed to overcome the limitations of vector control techniques (*refer* to Table 7) [105], [106]. Later, this topology has been adopted for variable speed wind electric system (WES) and high voltage direct current (HVDC) transmission systems. Besides that, the topology has been used to relieve the congestion in an interconnected system [107], provide a soft open point for the distribution system [108] and share power in a low voltage DC grid [109].

1) WIND ELECTRIC SYSTEM

The first application of synchronverter for WES has been employed in the back to back power converters of variable speed WES [110]. Where the machine side converter (MSC) and the grid side converter (GSC) have been operated as synchronous motor and generator respectively. The DC link voltage is maintained by MSC to avoid overvoltage due to continuous operation of wind turbine after a grid fault. Whereas the maximum power from the wind turbine has been extracted by GSC using the optimal tip speed ratio. However, in another work, the operation of GSC and MSC has been swapped based on the network interconnection (islanded/grid-connected) [111]. The presence of DC-link decouples the MSC and GSC which allows independent operation of both the synchronverters.

Furthermore, the synchronverter control has been compared with the vector control for control of a grid connected WES. Where the synchronverter strategy has enhanced the ancillary services provided by WES, like energy curtailment, power factor correction and power reserve [112].

2) HIGH VOLTAGE DIRECT CURRENT

The offshore wind farms connected to the HVDC system are vulnerable to sub-synchronous resonance, resonance at harmonic frequencies and poor dynamic response due to the absence of rotating inertia. The absence of PLL and cascaded loops in synchronverter can reduce the potential interaction between them. Hence synchronverter has been used to mitigate the sub-synchronous oscillations and improve the stability margin of the off-shore WES and HVDC system [22], [23]. Similarly, the synchronverter based HVDC has been used to enhance power transfer capacity between interconnected weak AC systems. The power transfer capacity has increased from 0.77 pu with synchronverter as opposed to 0.39 pu with the vector control for a small change in power [82]. Thus, the HVDC system with synchronverter control has outperformed the vector control strategies [113].

Furthermore, the transient stability of a multi-machine AC system with the synchronverter based HVDC has been investigated. The stability margin of the neighbouring multi-machine AC system has been improved with the synchronverter based HVDC [114]. A bang-bang controller has been proposed to generate a modulation signal based on the load angle variation of synchronverter. The modulation signal has been added to the synchronverter model to enhance the transient performance of the HVDC system. As a result, the critical clearing time has been increased from 200 ms to 300 ms with the proposed BB control [115].

C. DISTRIBUTED GENERATION INTEGRATION

Another important application of synchronverter is to integrate DG sources like solar photovoltaic (PV) [116]–[119], energy storage systems [120] and electric vehicles (EV). The synchronverter control has been used to integrate solar PV system with active power and DC link voltage regulation. The inertia of the system has been dynamically varied by using a derived inertia function. However, the variation of inertia had a minimum influence on the output of the synchronverter [121]. As the voltage profile of a weak grid traverse between extremities, an appropriate ESS with synchronverter control can be used to maintain the voltage stability [96].

Apart from VSC, a dual active bridge with synchronverter control has been investigated for grid integration of ESS [122]. Furthermore, the presence of single-phase loads in a domestic microgrid requires a neutral line for the connection. So, a three-phase four-wire inverter with synchronverter control has been proposed for grid integration of DG. An independent neutral line control has been proposed using the bidirectional DC-DC converter which acts as a current sink during the system unbalance [123].

Recently, synchronverter technology has been used to control the charging and discharging of EV batteries with an integrate H^∞ drepetitive controller [124]. A V2G charging

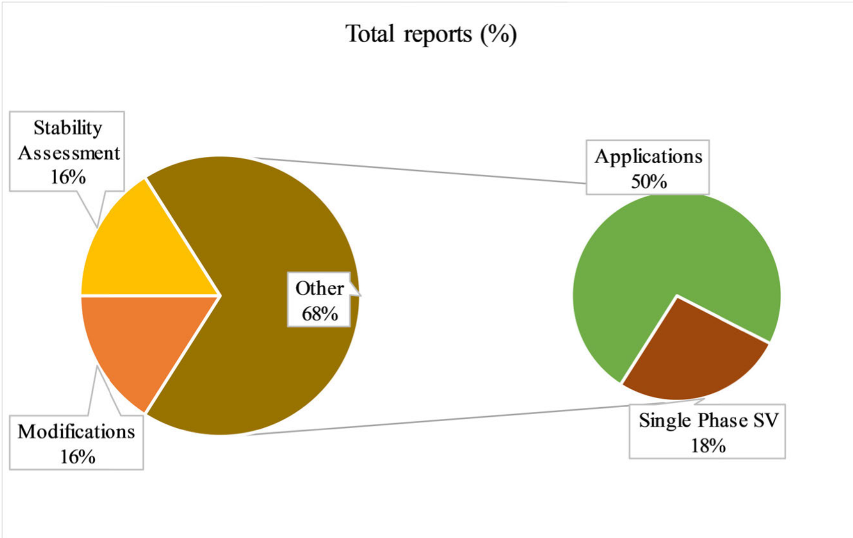

FIGURE 16. Analysis of scope of reported works.

station has been designed with synchronverter technology having dynamic droop capability. The droop values are assigned considering the instantaneous SOC of the battery pack. Since the high droop gain will result in the deep discharge of the battery pack during a low-frequency event [65].

D. POWER QUALITY ENHANCEMENT

1) HARMONIC COMPENSATION

In a multiple DG environment with non-linear loads, improper sharing of harmonic currents can lead to the operation of over current protection. So, a finite gain repetitive control (RC) has been proposed to vary the virtual output impedance of synchronverter for harmonic current sharing. The gain of RC at the harmonic frequencies of interest has been varied to modify the effective impedance of the converter [67]. Similarly, a resonant harmonic compensator has been proposed to mitigate the voltage harmonics for the integration of DG. The harmonic compensator has been derived through harmonic analysis to have good selectivity and modularity [111]. A virtual capacitance has been introduced in series with the output inductance of the inverter to reduce the THD of the output voltage. Particle swarm optimization algorithm has been used to optimize the virtual impedance for capacitive behaviour. As a result, the THD of output voltage has been reduced by 1.22% [125].

2) REACTIVE POWER COMPENSATION

Reactive power compensation plays a vital role in maintaining the voltage profile of the grid under steady-state and transient conditions. The overexcited synchronous machine under no-load operates as a synchronous condenser by injecting leading reactive power into the grid. Although the power grid is dominated by modern FACTS devices, the synchronous condensers are being used in remote power systems due to its robustness and low cost [126]. The STATCOMs with synchronverter control eliminates the need for PLL and are perceived as a synchronous condenser from the grid side.

Hence, the synchronverter strategy has been applied to control the operation of STATCOM for reactive power compensation and voltage support [27]. A droop mode operation has been proposed to share the reactive power among the parallel operated STATCOMs. In another work, the original synchronverter has been reconfigured to realize the operation of a static var compensator (SVC) and power system stabilizer [127]. The RPL has been controlled to ensure no real power exchange with the grid for the operation of SVC. Meanwhile, the RePL has been used to regulate the voltage and dampen the low-frequency oscillations. The use of synchronverter to mitigate other power quality issues like voltage sag, voltage unbalance, voltage swell, frequency oscillation [128] are yet to be reported.

VI. CURRENT TREND AND FUTURE DIRECTION

A. SYNOPSIS

1) MODIFICATIONS

The application of synchronverter in various domains has received major attention in the recent past (16%). Although the initial works on synchronverter have focussed on addressing the drawbacks of original synchronverter through appropriate modifications. Significant efforts (18%) have been made to conceptualize and develop the single-phase synchronverter with the increase in trend of residential solar PV plants (*see* Fig. 16).

2) STABILITY ASSESSMENT AND PARAMETER TUNING

The works on stability assessment of synchronverter contribute to a share of 18% (*see* Fig. 16). The frequency domain and time domain analysis for stability analysis of

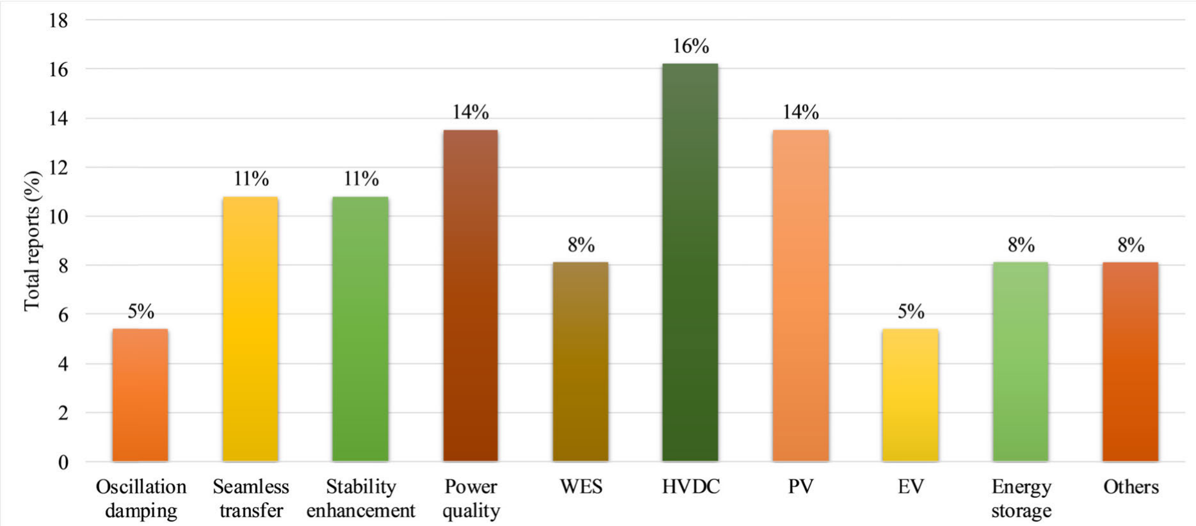

FIGURE 17. Breakdown of synchronverter technology adopted in various applications.

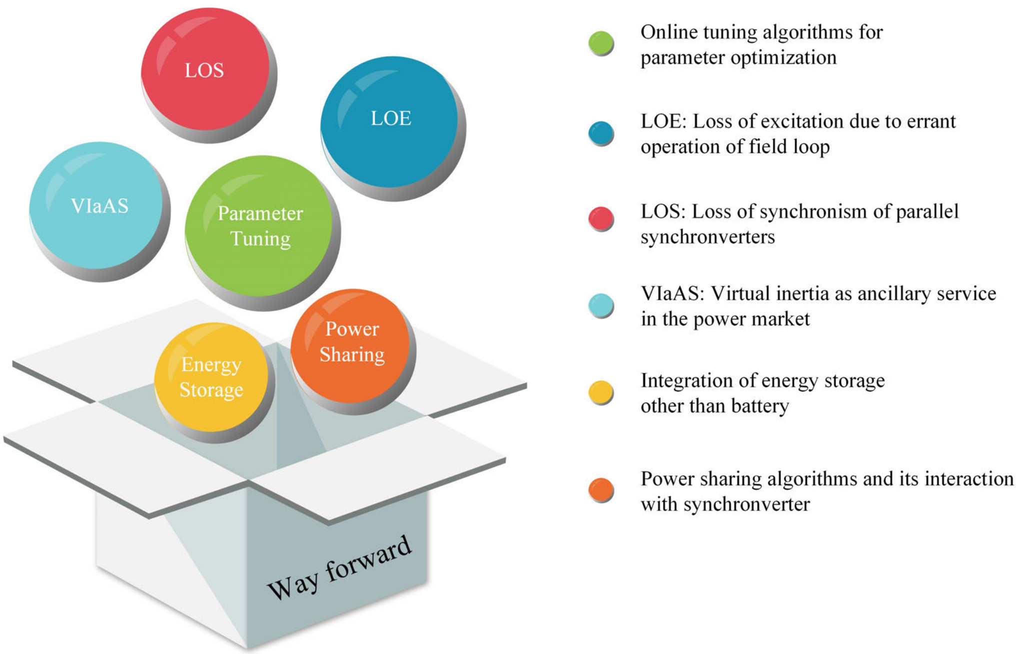

FIGURE 18. Anticipated future research direction on the control and adaptation of synchronverter.

synchronverter have been extensively reported. Meanwhile, the use of the direct method based on TEF has also been reported by a few researchers. The offline parameter tuning approach by utilizing the empirical relationships has been predominantly used and leaves room for the development of online tuning algorithms.

3) APPLICATIONS

The application of synchronverter for various systems has been one of the main domain of research (50%) (*see* Fig. 16). Among those applications, the works on HVDC cumulatively contribute to a higher percentage followed by power quality enhancement and solar PV systems (*see* Fig. 17). The trend indicates that the research on synchronverter leaves behind ancillary services, energy storage system integration and EV charging for further research.

B. FUTURE PERSPECTIVES

The following recommendations are made based on the critical review presented in the previous sections along with the anticipated research direction (*see* Fig. 18).

1) MODELLING AND ANALYSIS OF SYNCHRONVERTER

With the ever-increasing share of RES in the energy mix, it is critical to mimic the exact operation of SM to preserve the well-established control principles of the power system. The parameters of synchronverter underpin its ability to exert similar physical properties of an SM. Lately, online optimization techniques have been used to optimize the value of inertia and damping coefficient of VSGs to achieve desired response [71], [72]. Although certain efforts have been made to optimize the parameters of synchronverter, the online parameter tuning methods are yet to be reported. Thus, efficient parameter optimization techniques could be developed to meet the trade-off between stability and dynamic response.

On the other hand, loss of excitation is an undesirable phenomenon observed in SM which forces the machine to operate as an induction motor by drawing reactive power from the grid. However, this phenomenon can also affect the synchronverter which is based on the empirical model of SM [13]. Hence, the effect of the excitation loop (under-excitation and loss of excitation) on this potential instability of synchronverter needs to be investigated. The damper windings are the critical element of an SM which ensures stable operation under transients. Recently, the effect of damper windings has been induced to VSG and its ability to operate as a power system stabilizer [129]. However, the synchronverter model with damper windings is yet to be analysed. It can lead to various investigations on employing damper windings for applications like oscillation mitigation and enhancement of stability margin.

2) ENHANCING VIRTUAL INERTIA WITH ESS

It is a well-known fact that the virtual inertia offered by synchronverter is limited by the energy storage element in the DC link. A bulky capacitor in the DC link increases the cost and affects the dynamics of the system. Hence, the anticipated inertial response exerted by RES with synchronverter is comparatively low. However, interfacing ESS with the grid using synchronverter will enhance the inertial response due to its higher energy storage. Thus, synchronverter can be employed to ESS requiring power converters for grid interface. It includes flywheel energy storage, compressed air energy storage, battery, ultracapacitor and variable speed pumped hydro storage (PHS).

The combined use of hidden inertia emulation in the variable speed PHS and virtual inertia emulation by synchronverter can support large power grids during a frequency event. Besides that, the ultracapacitor with faster response rate and high power capacity can be a better option to support isolated microgrids. To date, the synchronverter strategy has only been adopted to control the battery energy storage system. However, the synchronverter strategy is a potential alternative to the vector control techniques which are predominantly used to interface the ESS with the grid.

3) VIRTUAL INERTIA AS ANCILLARY SERVICE

In a conventional power system, the inertial requirement during transient events is satisfied by SM freely, so, the inertia has never been treated as a tradable service. However, the development of the market for virtual inertial services shortly will attract investments in sophisticated equipment with advanced control strategies. The lack of inertia in RES dominated power system will probably lead to high demand for virtual inertia. Exhaustive research has been carried out in the past to emulate the virtual or hidden inertia by de-loading solar PV and WES by a certain factor [1]. However, the continuous de-loaded operation can lead to revenue loss which may overshadow the benefits of de-loading. Thus, RES with synchronverter can eliminate de-loading and trade in virtual inertia as an ancillary service to generate additional revenue.

Meanwhile, vehicle to grid (V2G) technology is proven to have promising performance in delivering ancillary services [130], [131]. Hence the charging station with synchronverter technology can be used to provide virtual inertia as an ancillary service when the car is parked at the office or home. However, the trade-off between the lifetime of the battery and the profit earned through ancillary services is imperative.

4) PARALLEL OPERATION OF SYNCHRONVERTER AND SM

The conventional power system is dominated by SM whose control strategies and dynamic response vastly vary with the control strategies of power converters. Although the virtual inertia emulation strategies are developed to match the dynamic behaviour of SM, they differ in physical attributes. A synchronverter based system injects power rapidly but SM has an inherent mechanical time delay. The difference in response time may lead to transients in the power system when the penetration of synchronverters is high.

A few works have reported a decrease in the stability margin of the system with high penetration of synchronverters. This is probably due to the negative interaction between the control loops of synchronverters, which are vulnerable to the variation of control parameters. Thus, it is recommended to investigate the steady-state and transient behaviour of such a power system to develop a standard interface between both. By far, the works on synchronverter assumes a perfect knowledge of real and reactive power set points, which is not suitable for isolated microgrids. The optimal power sharing between the synchronverters is yet to be investigated by considering the dynamic interaction of power sharing technique and the synchronverter. Furthermore, the transient stability and loss of synchronism of parallel operated synchronverter in isolated microgrid remain unattended.

5) PROTECTION ISSUES

The paradigm of distribution system protection is changing with the increase in penetration of DG sources. The conventional radial distribution system with unidirectional power flow is transiting towards active distribution system with bidirectional power flow. This transition has led to challenges like time-varying fault current, poor protection coordination and bidirectional current flow [132]. The converter-interfaced DGs have different behaviour under fault when compared to SM. Where its fault current contribution is limited to their rated capacity by the inner current control loop. It is often lower than the actual relay setting which may not be sufficient to operate the overcurrent protection relays. Nevertheless, the synchronverters do not have inherent current control capability. It is expected to behave like an SM with high fault contribution. However, the protection coordination of DGs with synchronverter in the distribution system is yet to be reported. Lately, the seamless transfer of synchronverters between grid connected and autonomous modes have been analysed. Thus, future research on protection coordination along with the seamless transfer can solve the protection issues with synchronverter fed DGs.

6) SYSTEM SECURITY

The control and coordination of DGs in a microgrid takes place hierarchically with primary, secondary and tertiary controls. These strategies can be classified as centralized and decentralized control strategies. Typically, the secondary and tertiary control strategies are centralized whereas the primary control is decentralized. However, centralized control has advantages like better tracking of references and accurate regulation of voltage and frequency. The synchronverters operating in parallel can communicate with each other to adjust their outputs for better regulation [133]. The parallel operation of synchronverters in different areas with centralized controls are yet to be reported. Thus, the anticipated increase in penetration of synchronverters in modern power system demands further research to develop centralized control strategies.

Furthermore, they require a high bandwidth communication channel to communicate with each other over a wide area network (WAN). However, these communication channels are vulnerable to cyber threats. The communication protocols adopted in power system including MODBUS and distributed network protocol do not have cryptographic functions to protect the information propagated through WAN [134]. Thus, research on cyber threats to parallel operation of synchronverter fed DGs is another potential field which requires further attention.

VII. CONCLUSION

The shift from conventional power generation system towards the power electronically dominated system has given rise to a new paradigm called as virtual inertia. The synchronverter based virtual inertia emulation technique is by far the closest resemblance of a synchronous machine. The increase in penetration of synchronverter into the power system would increase the effective inertia and enhance transient stability. Thus, a critical analysis of the control and stability of synchronverter is necessary to catalyse and aid the transition towards a modern power system deprived of inertia. In line with the demand, a comprehensive review on synchronverter has been presented in this paper by collating literature from 2009 to this date.

A critical review of modifications made to the synchronverter has been presented to accentuate the outcomes and limitations of every modification. A decision matrix for parameter tuning has been presented by analysing the movement of eigenvalues presented in the references. It will function as a handout to achieve a trade-off between dynamic performance and stability. The adoption of synchronverter for various applications has been classified and critically analysed based on topologies used. Furthermore, a synoptic overview of the research progress has been presented to emphasize the domains which are left unattended. To the end, a brief discussion on future research direction is presented based on the research gaps perceived during the review phase. Nevertheless, this paper would serve as a reference for the control and design of synchronverter and steer future research in this field.

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