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A Review on Synchronverter Technology and Its Application to Grid Connected EV Charging Station

Abstract: - The usage of the word Power quality in recent times acquired intensified interest due to the complex industrial processes. The usage of intelligent tools to improve power quality is increasing day by day, as assumption of present day power system as a linear model is unsatisfactory. This paper deals with analysis of Differential Evolution (DE), Hybrid Differential Evolution (HDE) and Variable Scaling Hybrid Differential Evolution for harmonic reduction in the source current with optimal tuning of PI controller gain values. Shunt Active power Filter is one of the better solution to suppress the source current harmonics which are induced into power system because of nonlinear loads. Current controller called HBCC is considered for gating operation of switches in Voltage Source Inverter. The Intelligent tuned PQ theory is used for reference current generation. The then obtained compensating currents are injected at point of common coupling for current disturbance mitigation. Simulations of MATLAB/SIMULINK environment of the present work shows the efficacy.

Keywords: Shunt Active Power Filter (SAPF), Intelligent Instantaneous Active and Reactive Power (IPQ) Theory, Hysteresis band current controller (HBCC), Variable Scaling Hybrid Differential Evolution (VSHDE) and Total Harmonic Distortion (THD), Power Quality (PQ).

I. INTRODUCTION

Day-to-Day electric vehicles are gaining importance for mobility in terms of energy utilization and the environmental impact. This growing demand has made the utility to think in providing the charging infrastructure and the ways to provide the additional energy requirement. With the advent of technologies to connect the vehicle to grid and provisions of directional power flow between them has opened new opportunities viz. active power regulation, load balancing and frequency control etc.

As the growth trend of EVs connected to grid are increasing, the stability of the power system is affected. Earlier the stability of power system depends in the large synchronous machine. Therefore the major problem here is the renewable energy sources or EVs connected to grid through power electronic converted which were unable to provide required inertial behavior as provided by synchronous machines. So, in the overall all system stability point of view with high penetration of grid connected power electronic interfaced EVs would be affected by the power fluctuations and severe faults. So, in order to address this issue, researchers has proposed synchronverter technology to realize synchronverter behavior. Hence, a synchronverter technology based V2G charging station can behave as grid connected virtual synchronous machine. In this paper, a brief review of synchronverter technology and its applications to a vehicle to grid connected charging station is presented.

Organization of paper is as follows: Section II presents the modelling and control blocks of synchronverter is presented. Application of this technology for integration of distributed energy resources is also presented in this section. Basic concept of vehicle to grid connected charging station and its effect on distribution system is analyzed in section III. In section IV, modeling and control of synchronverter based V2G charging station is reviewed. The key issues identified in this literature review are concluded in section V.

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II. SYNCHRONVERTER TECHNOLOGY

A grid connected distributed generation with power electronic interface having an energy storage device in its DC bus can be used to replicate different properties of a synchronous generator. The basic building block which includes the control block and power block are shown in Fig. 1. In this section, modeling and control of synchronverter is presented, which will help in understanding the techniques for assessing the stability [1]. The ability of synchronverter to emulate the inertial response for improved voltage stability in grid connected distributed energy resources is discussed in later parts of this section.

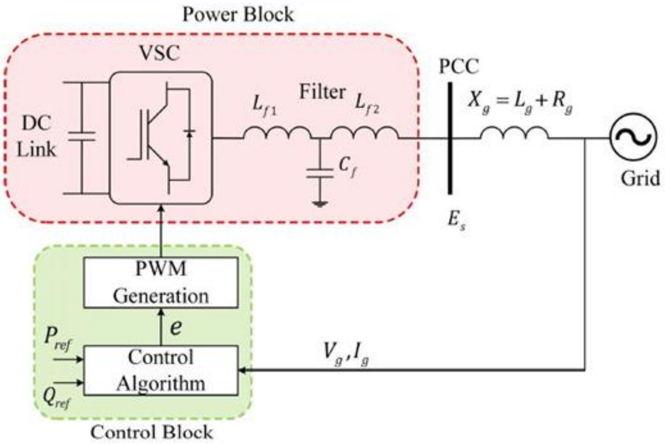

Fig. 1. Power block and control block of synchronverter

A. MODELING AND CONTROL OF SYNCHRONVERTER

The dynamic model of the round rotor synchronous machine is considered for empirical modelling of synchronverter technique [2]. The model considered has distributed winding on stator side and concentrated winding on rotor side. It is assumed that rotor has single pole pair, and effect of magnetic saturation and damper windings is neglected. The modelling equations related to syhcronverter are given below:

$$\mathrm{v} = \mathrm{e} - \mathrm{i}\mathrm{R_S} - \mathrm{L_S}\frac{\mathrm{di}}{\mathrm{dt}} \qquad (1)$$

$$\mathrm{e} = \mathrm{M_f} \mathrm{i_f} \dot{\theta} \widetilde{\sin\theta} - \mathrm{M_f}\frac{\mathrm{di_f}}{\mathrm{dt}}\widetilde{\cos\theta} \qquad (2)$$

$$\frac{\mathrm{d}\omega}{\mathrm{dt}} = \frac{1}{\mathrm{J}}(\mathrm{T_m} - \mathrm{T_e} - \mathrm{D_f}\omega) \qquad (3)$$

$$\mathrm{T_e} = \mathrm{M_f}\mathrm{i_f}\langle \mathrm{i}, \widetilde{\sin\theta}\rangle \qquad (4)$$

$$\mathrm{P} = \mathrm{M_f}\mathrm{i_f}\dot{\theta}\langle \mathrm{i}, \widetilde{\sin\theta}\rangle \qquad (5)$$

$$\mathrm{Q} = -\mathrm{M_f}\mathrm{i_f}\dot{\theta}\langle \mathrm{i}, \widetilde{\cos\theta}\rangle \qquad (6)$$

Where, v is the synchronverter terminal voltage, e is the induced stator voltage, $\mathrm{i_f}$is the rotor field excitation. L, M and $\mathrm{L_f}, \mathrm{M_f}$ are the self and mutual inductances on stator side and rotor side and $\mathrm{R_s}$ is the stator resistance. T_m, T_e, D_f and J are mechanical torque input, electromechanical torque, frictional coefficient and virtual inertia respectively. In (4), T_e is produced by the interaction of stator and rotor fluxes, active and reactive powers can be computed from (5), (6).

In Fig. 4, real power loop and reactive power loop are added to the above model to replicate the complete behavior. For steady state operating equilibrium, the inner loops are tuned to higher bandwidth than the outer once [3]. For valid P-f and Q-V relationship, the models output impedance is considered to be high. The modified equations are as below:

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

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

Where, ω_n, ω represents synchronverter nominal frequencies and V_g, V_n are actual and reference voltage of grid.

In (3), speed governor term ($D_f\omega$) in (7) is modified to reflect the P-f droop, where D_f is power droop coefficient [4]. Eq. (8) realizes the direct dependence of reactive power on the terminal voltage, to reflect the Q-V droop, where D_q is the voltage droop coefficient.

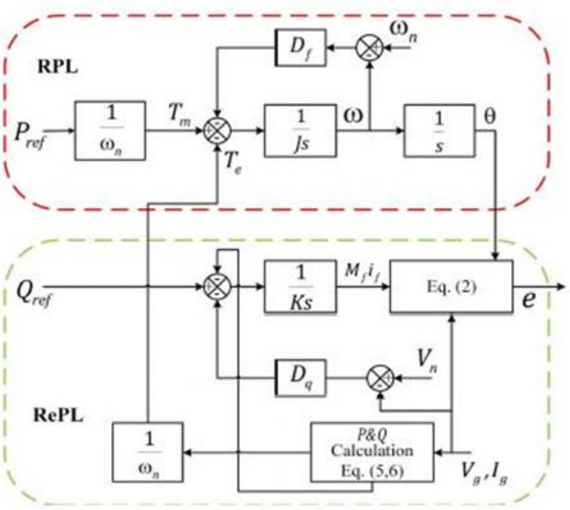

Fig. 2: Synchronverter model with real power loop and reactive power loop

In order to analyze the stability of the system under various disturbance scenarios, the nonlinear equations presented in (7), (8) are linearized around the initial equilibrium operating point for a small disturbance in input. The small signal model can be represented either by state space matrices or transfer functions. As in grid connected operation, the state space matrices are considered to be constant due to unchanged in equilibrium operating conditions [5]. Fig. 3, represents the small signal model of synchronverter.

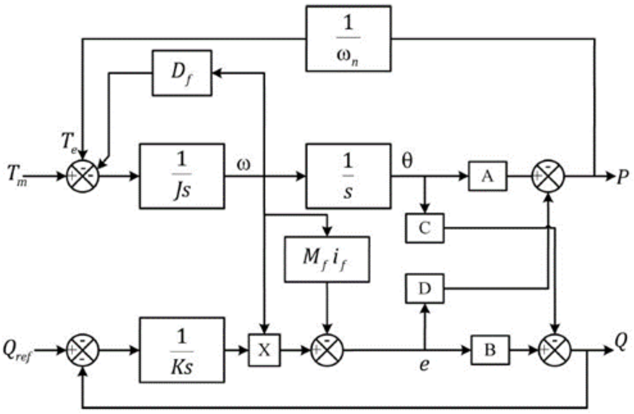

Fig. 3: Small signal modelling of synchronverter

But the synchronverter topology has various issues related to coupled droop and damping control, deviation in steady state power, absence of current control and self-synchronization (necessity of phase locked loop during initial synchronization). So, considering the above short comings, the topology has been modified to attain the desired response. As per the grid code, the change in power required determines the power droop coefficient and cannot be locally changed. The relation between the change in power to change in frequency is given by (9).Dynamic response of original synchronverter is adjusted by adding a derivative term, which requires modification of steady state droop characteristics [6]. So, in Fig. 4, an augmented synchronverter model for damping correction loop to decouple the power droop and damping coefficients [7].

$$\frac{\Delta \mathrm{P}}{\Delta \omega} = -\mathrm{D}_{\mathrm{f}}\omega_{\mathrm{n}} \tag{9}$$

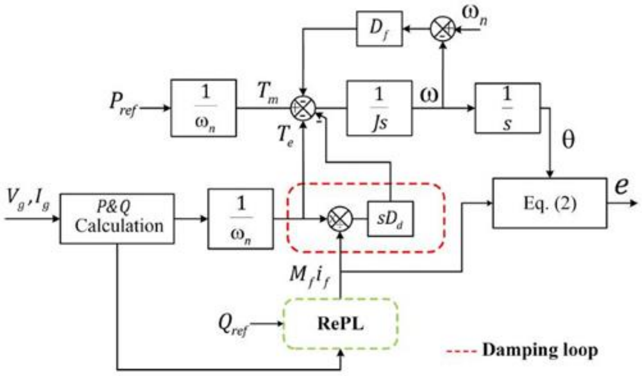

Fig. 4. Augmented synchronverter model with damping correction loop

The original synchronverter model has frequency-voltage regulation mechanism by assuming a pure inductive impedance. But on the other hand, in a weak grid, resistance will be considerable higher than the reactance which results in cross coupling between P-V and Q-δ [8]. This can be overcome by increasing filter inductance, which in turn increases the line inductance.

The techniques to emulate the inertia lies on various forms of swing equation governing the electromechanical systems. In synchronverter, the relationship between P and δ is nonlinear. In (10), a linearized swing equation to control the real power angle is given [9].

$$\frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} = \mathrm{R}_{\mathrm{c}}(\delta^* - \delta - \mathrm{D}_{\delta} - (\omega - \omega_{\mathrm{n}})) \tag{10}$$

Where, $\mathrm{R}_{\mathrm{c}}(\mathrm{s}^{-1})$ is rate of change of frequency (ROCOF), D_{δ} is the droop constant and δ^*, δ are reference and actual power angles.

Similar to synchronous machine, synchronverter also has the property of self-synchronization. But, initial grid angle is required for initial synchronization using phase locked loop (PLL). But this methods suffers from drawbacks in respect of complexity in tuning, stability margin and dynamic performance etc. [10]. This can be achieved with the use of PLL. In [], the first of self-synchronization strategy has been proposed. The virtual current for initial synchronization can be obtained from (11) and is as shown in Fig. 5. When the grid voltage matches (V_g) the induced emf (e), the synchronization is achieved. In order to eliminate the steady state error in torque, a PI controller is added to frequency control loop [11].

$$\mathrm{i}_{\mathrm{V}} = \frac{1}{\mathrm{sL}_{\mathrm{V}} + \mathrm{R}_{\mathrm{V}}}\left(\mathrm{e} - \mathrm{V}_{\mathrm{g}}\right) \tag{11}$$

Where, $\mathrm{L}_{\mathrm{V}}, \mathrm{R}_{\mathrm{V}}$ are virtual inductance and resistance respectively.

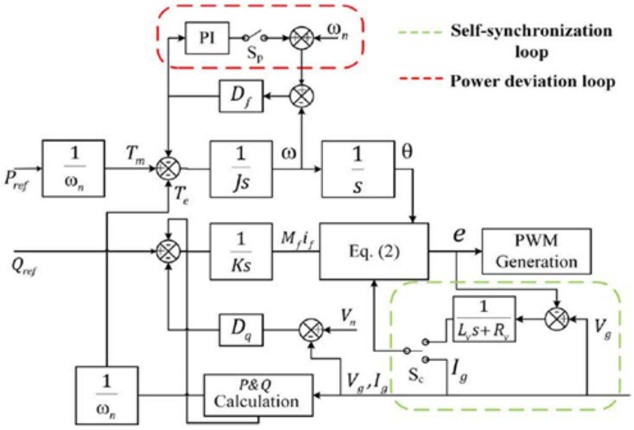

Fig. 5. Synchronverter model modified for self-synchronization

In the next section, the application of synchronverter technology for integration of distributed energy resources is presented.

B. APPLICATION OF SYNCHRONVERTER TECHNOLOGY FOR INTERGRATON OF DERs

The capability of synchronverter to mimic desired characteristics of a synchronous machine has driven various researchers to apply this concept to different applications such as transient stability improvement, integration of distributed energy resources, power quality enhancement etc. In this section, application of synchronverter technology for voltage stability improvement in grid connected DERs will be discussed.

In [12]-[16], the application of synchronverter for integration of energy storage systems, solar PV systems and electric vehicles. The DC link voltage regulation and active power control is achieved by synchronverter control. The virtual inertial behavior of synchronverter makes it dynamically change the inertia of the system. From [17], it is observed that a weak grid is effected by voltage variations and oscillates between extremes. In such a scenario appropriate energy storage element with synchronverter control can be used to maintain voltage stability [18]. The synchronverter also finds its application in charging and discharging of electric vehicle batteries with robust controllers [19]. The dynamic droop capability associated with synchronverter technology is used for the design of electric vehicle connected to grid connected charging station. As the low frequency scenarios results in deep discharge of batteries, the instantaneous state of charge (SOC) of the battery is considered to set the droop values [20]. So, in the next section, a brief review on electric vehicle charging station is presented.

III. VEHICLE TO GRID CONNECTED CHARGING STATIONS

Due to the environmental issues like greenhouse gas emission, decrease in fossil fuels reserves, crises in oil and increase energy costs lead to the paradigm shift in utilization of plug in hybrid and electric vehicles for their mobility [21]-[23]. Usually large scale deployment of electric vehicles requires large infrastructure for charging and discharge them. Day-to-day, more number of vehicles are connected to grid, it made to take the opportunity to use them for grid support by acting as energy storage system. In [24], utilization of PEVs as vehicle to grid (V2G) connection in discharge mode and grid to vehicle (G2V) connection in charging mode. It gained the attention of vehicle owners and grid operators. Of all these benefits discussed, in the next subsection, we will present the effect of V2G charging station on the distribution system and also the control strategies for the V2G connected charging stations.

A. EFFECT OF V2G CHARGING STATIONS ON UTILITY

The basic components in an electric vehicle to grid connected system are shown in Fig. 6 [25]. It constitutes of renewable sources of energy, charging facilities, availability of charging facilities at various locations, aggregators and independent system operators, bi-directional electrical energy flow, communication between the vehicles and aggregators, intelligent metering control system and battery management system in electric vehicle.

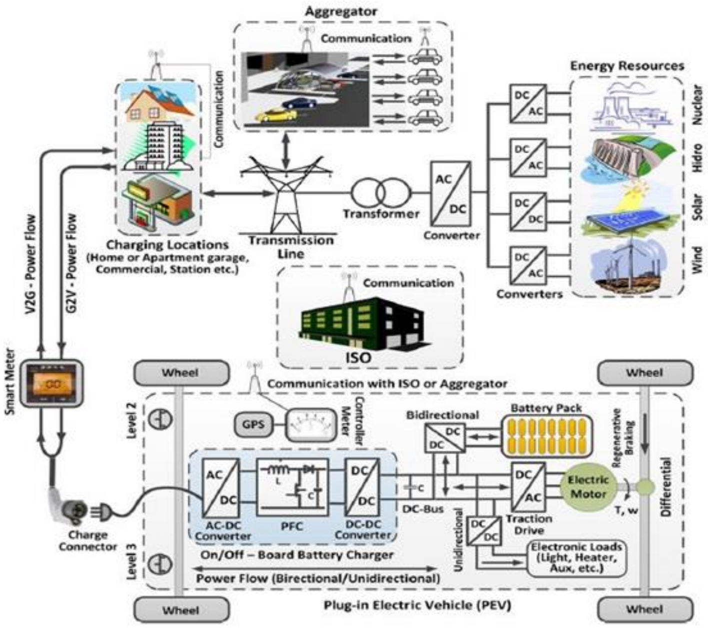

Fig. 6. Components in vehicle to grid connected system

There are different types of power flow methods in a V2G system [26]-[30]. One way is the unidirectional power flow from EV to grid. It has the advantage of improving the performance of the system in terms of providing the grid regulation and spinning reserves. The other way is the bi directional power flow between the EV and grid. This has more advantages than the unidirectional power flow method. In both these methods, communication systems plays a major role. The above methods are adopted keeping in view to reduce the greenhouse gases, improving the quality of power and maximizing the profits.

Now, in order to manage the power flow and energy in V2G systems, different models and management strategies have been proposed in the literature. In [31]-[32], centralized V2G management have been proposed. In this type of strategy, the charging and discharging are controlled by considering the demand in the grid and the energy of EVs available at a location. The charging station and grid works in coordination to adjust the peak load in the system. But when the vehicles are wide spread and the EVs cannot be controlled centrally, In this case, independent V2G management strategies have been proposed [33]. This type of management should have three levels of scheduling viz., scheduling of transmission, distribution and EV control center. The last of these is the battery pack replacement management. In [35]-[36], reported a battery solution, which gives the best ability of energy storage during, over voltage, under voltage and braking conditions. This management strategy is similar to centralized V2G management.

Reviewing the various advantages of V2G technology, backup energy for homes, active power support and ancillary services are found to be predominant [37]-[39]. Besides the advantages degradation of the battery, investment cost and social barriers are posing challenges to this technology [40].

IV. SYNCHRONVERTER BASED CONTROL STARATEGY FOR V2G CONNECTED CHARGING STATIONS

In this section, synchronverter based control strategy for V2G connected charging station will be discussed. In [34], the modeling of control of a V2G charging station using synchronverter technology is proposed. The charging station presented has different components such as i) control unit, ii) synchronverter, iii) DC unit. These synchronverters are used as AC/DC interfaces between the grid and the charging station. The reference power and imaginary friction coefficient are determined by the control unit. It consists of adaptive droop coefficient unit, capacity calculation unit and the T-S fuzzy control unit. The DC buses to which the EVs are connected and the DC-DC converters constitutes the DC unit. The frame work of charging station is shown in Fig. 7.

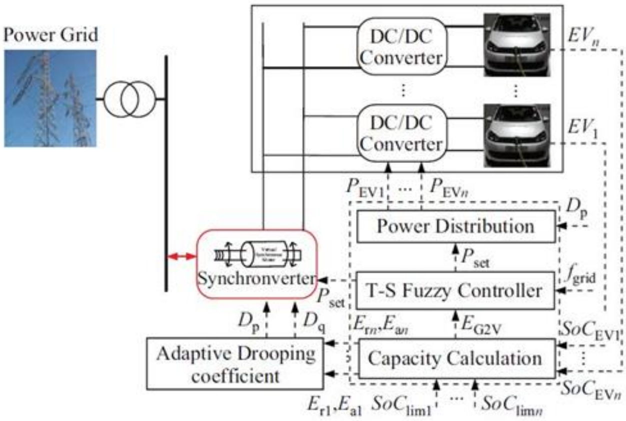

Fig. 7. Charging station conceptual framework

The process involved in the charging station framework proposed above are summarized as the capacity calculation unit (CCU) receives information about the state of charge, capacity of all electrical vehicles. Then the CCU computes the available and required energy of all EVs batteries and the V2G charging station unit. Then based on the system frequency and the total energy required by the V2G station, T-S fuzzy controller computes the reference power for the charging station. Based on the reference power, appropriate frequency droop characteristic for the synchronverter is selected. With these parameters, reference charging/ discharging power for all EVs and final reference power point for charging station is computed. As per the above procedure synchronverter helps in automatic interaction between the grid and the electric vehicle.

The synchronverter model presented in Fig. 5, is used control of grid connected electric vehicle. The frequency droop control which is shown in upper part, is designed for regulating charging and discharging of the real power of the charging station. For voltage support, the reactive power required for the grid is provided by voltage droop control loop.

The important features of this proposed methodology are the charging station reference power is decided by the T-S fuzzy controller by using grid frequency (which is computed the synchronverter) and individual EVs charging demand. In order to adopt to the change in energy capacity of DC bus, an adaptive frequency drooping coefficient mechanism which modifies the frequency droop characteristics of synchronverter. The charging station output power is determined by frequency droop control characteristics of synchonverter in droop mode. Finally, the proposed control strategy using synchronverter transformed a grid connected charging station to act as large synchronous machine. It also can introduce inertia and damping into grid, which makes the grid operation smoother.

V. CONCLUSIONS

Grid connected EVs are increasing day to day. The static converter interfaces utilized to connect these vehicles to grid posing issues to the overall stability of the system. This is due to the non-inertial behavior of these technologies. Conventionally, the synchronous machines inertial support to the system during severe disturbances. So in this paper, synchronverter technology which could mimic the synchronous machine behavior is reviewed. The benefits of application of this technology to the grid connected electric vehicle charging station is studied. This helped in improving the stability, reliability and efficiency of the electric grid.

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