International Journal on Emerging Technologies 10(2): 08-14(2019)

ISSN No. (Print) : 0975-8364
ISSN No. (Online) : 2249-3255

Review of Control Techniques in Intertied AC- DC Hybrid Power System

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(Received 02 April 2019, Revised 21 June 2019 Accepted 29 June 2019)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: Today, conventional power system is evolving to smartgrids, where intertied hybrid power system may additionally make the distribution more effective with high penetration of renewable sources. Intertied hybrid system with combination of ac and dc source along with load is the most economic solution for future power. Power sharing and adequate voltage/frequency control are the most widely recognized functions of ac and dc hybrid power system (HPS). For such intertied hybrid power system, power management strategies are one of the most critical operation aspects. This paper presents an overview of power management strategies for an intertied hybrid power system, which includes centralized and decentralized control techniques. Finally, discussion and recommendations of power management strategies for the further research are presented.

Keywords: Intertied hybrid power system, Interlinking power converter, ac HPS, dc HPS

I. INTRODUCTION

Distributed generation has recently received a lot of attention as a potential solution to meet the increased demand for electricity, and to integrate more renewable and alternative energy sources. Therefore, the intertied hybrid power system (HPS) has emerged as a promising approach to integrate various distributed energy resources effectively. Different renewable sources like PV, wind generator, fuel cell etc. can be used to integrate along with storage to form HPS [1]. An intertied hybrid power system is defined as a part of distributed system which include distributed source along with storage and load to be operated either in grid connected mode or stand alone mode. An intertied hybrid power system is a flexible and effective approach to interconnecting ac and dc sources and load to achieve continuous and reliable power supply.

In the grid-connected mode, the operating voltage and frequency regulation is provided by the grid. The utility grid ensures a frequency regulation due to the rotating mass inertia of the large synchronous generators in the power system. Moreover, the amount of power exchanged between HPS and the grid is determined by the difference between the generation and load demand in the intertied hybrid power system. In other words, the grid is responsible for maintaining the power balance in the intertied HPS. Challenges associated with intertied HPS are modelling, monitoring, control, communication and power management [2-5]. In order to enhance the capacity of the distribution ac and dc HPS can be integrated together [6]. However control strategies for single dc HPS is simple as compared to combined ac-dc intertied HPS [7-9]. Adaptive control strategies can also be used to improve the system dynamics [10]. Therefore, the absence of the grid in the stand alone mode makes intertied HPS control more challenging [11]. In standalone mode, control strategy must be able to regulate frequency and voltage [12]. Due to the rotating mass inertia of large generators in conventional power systems, the grid offers a stiff and robust regulation of the operating frequency in grid-connected mode. The grid achieves this by supplying/absorbing the transient power difference during generation/load disturbances, with a negligible decrease/increase in the frequency during transients. In case of standalone operation of intertied HPS, the frequency and voltage regulation provided by the grid will no longer be available. Therefore, at least one DG unit must be responsible for the task of regulating the intertied HPS voltage and frequency. However, the power electronic converters used to interface the DG units have negligible inertia so fast acting energy storage devices, such as batteries, super capacitors or flywheels, are used to duplicate the effect of the rotating mass inertia in the conventional grid [13]. This energy storage device can be connected to the grid, through power electronic interfacing converters. The fast response of the energy storage enables the DG unit to react to any transient imbalance in the generation/load demand, while regulating the operating frequency and voltage [14]. Battery storage is commonly employed as the energy storage in intertied HPS applications due to its high energy density in comparison to the super capacitors and flywheels. Ideally, DG units must be controlled together to match the load demand at steady state. Accordingly, the battery storage in the intertied HPS neither supplies nor absorbs power at steady state to avoid depleting or over-charging the battery. Nevertheless, the battery storage can be controlled to supply power during peak load periods, when the load demand increases beyond the total generation, or to absorb the surplus power from the renewable energy resources, to maintain the power balance in the stand-alone intertied HPS Power quality of intertied HPS can also be improved by employing active power filter [15].

A brief review of various control strategies of intertied HPS has been performed in this paper. Many of the researchers are working in the area of control of intertied hybrid system with artificial intelligence techniques, coordination control, control of converter fed microgrids [16]-[19]. The dc HPS can also serve as charging stations for electric vehicles [20]. The research on intertied HPS control has mostly been focused on power management using centralized or decentralized control strategies. Control strategies for ac and dc HPS have been extensively researched. Most of the research has been pointed on ac and dc HPS's individual control rather than overall hybrid mode of operation.

The structure of this paper is as follows: Section II presents power management control and section III discusses control techniques. Section IV presents conclusion of the review.

II. POWER MANAGEMENT CONTROL

The Interlinking power converter (IPC) is power electronic interface used to interconnect ac HPS and dc HPS. Fig. 1 shows the system structure for intertied hybrid power system.

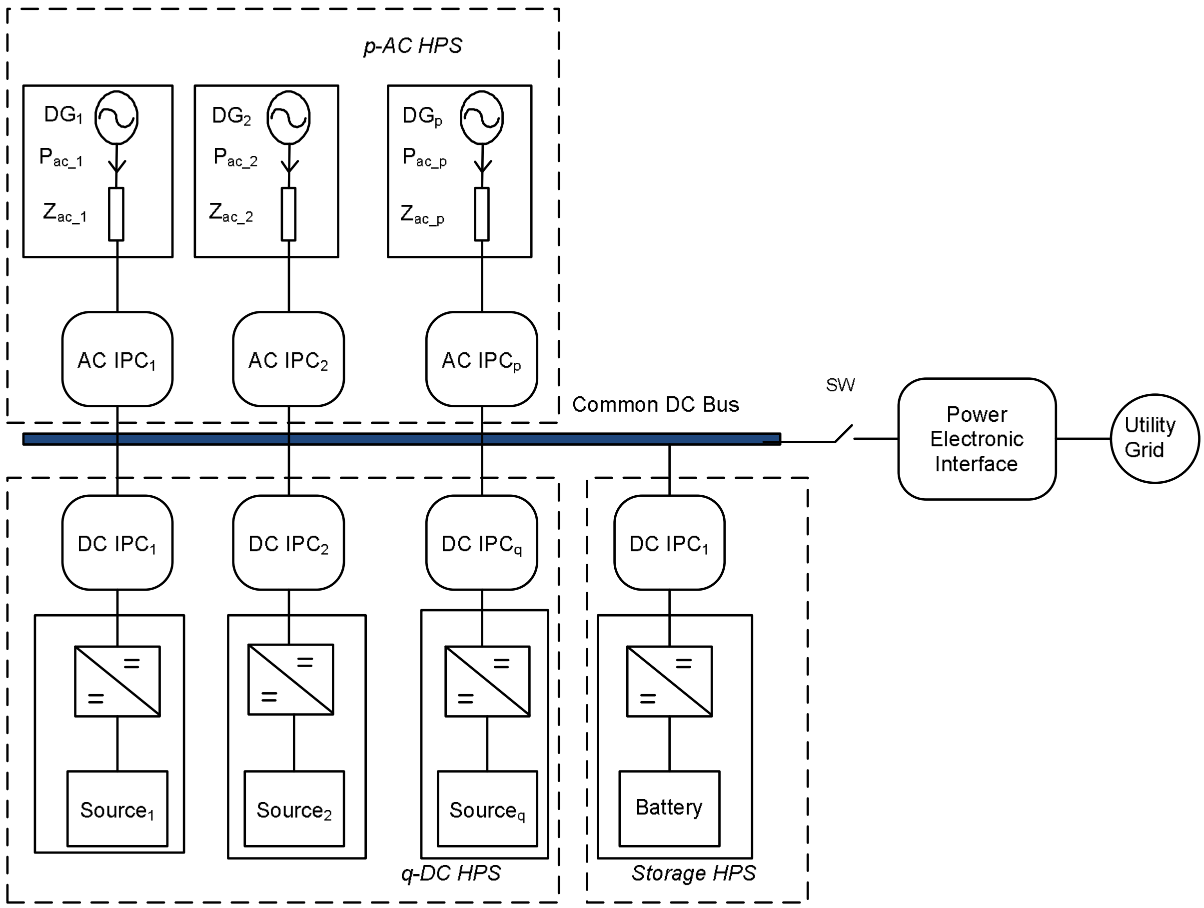

Fig. 1. Intertied HPS System structure.

In accordance to the direction of power flow, IPC can act as a rectifier or an inverter. The IPC controls the dc bus voltage under grid connected operation of intertied HPS. The controller should satisfy following conditions.

- Smooth transition between grid connected and stand alone mode of operation.
- Uninterrupted supply to critical loads
- Optimized control and power exchanges within the intertied HPS.

The research on control structure is gaining prominence. The main objectives of the control are to fulfil the appropriate active and reactive power-sharing among the HPS by integrating the power controllers, maintaining converter terminal voltage magnitude and frequency. Two types of control are discussed for intertied HPS in this paper.

A. Centralized Control

DC-AC converters are capable of operating in the PQ mode by determination of voltage and frequency reference from grid in grid connected mode [21]. However, in stand-alone mode, master-slave controller based approach can be used. In single master operation, a single master converter operates in voltage control mode as a voltage source converter while the other converters (slaves) operate in the PQ mode as current source converters [22]. The master converter is used to set the voltage and frequency references for the intertied HPS using droop control whereas slave converters inject specified active and reactive power.

B. Decentralized Control

Decentralized techniques are more popular these days; they incorporate droop control and its modified versions in order to achieve power sharing, bus voltage and frequency regulation. Here only by local information decides control actions so there is no need of communication among control entities. However, steady state deviation from the nominal values in frequency of ac HPS and voltage of dc HPS occur by using decentralized methods. Research on low voltage dc HPS, load sharing, power management, hierarchical control, wireless load sharing is carried out in many of the literature [23-26]. In respect of comparison to centralized control autonomous control, distributed control and coordinated control are attracting researchers to work in this area [27-29].

III. CONTROL TECHNIQUES

A. Conventional Control

In standalone mode, the intertied HPS operates separately from distribution network and the system operating characteristic rely mainly on DGs in the intertied hybrid ac/dc HPS [30].

The main aim of the control strategy is to realize a reasonable power allocation between the ac HPS and the dc HPS dynamically. In ac and dc HPS, the distribution of active power is realized based on P-f and P-V_{dc} droop characteristics as shown in Fig. 2. Conventional control strategy for an intertied HPS is a widespread technique for the decentralized control. Droop control results in proper voltage and frequency control and appropriate power sharing among ac and dc HPS. P-f droop characteristics for each ac sources is given by

$$f = f^{ref} + m_p P_{ac-p} \quad (1)$$

$$m_p = \frac{f_{min} - f_{max}}{P_{ac-p}^{max}} \quad (2)$$

$$m = -\frac{1}{k_{Pac}} = \frac{-\Delta P_{ac}}{\Delta f} = -\frac{P_{ac}}{f^{ref} - f} \quad (3)$$

Here *f* is the frequency of output voltage, f^{ref} is the reference frequency at no load, P_{ac-p} is generated active powers and m_p is droop slopes in the p^{th} ac source. For proper power sharing among sources in proportion to their capacity, the slopes of droop characteristic in each source is chosen inversely proportional to its capacity.

The control strategy of dc sources in a typical dc-HPS is comparatively simple. The controlling of dc sources in order to achieve proper voltage control and power sharing with droop characteristic is given by Fig. 3.

$$V_{dc-q} = V_{dc}^{ref} + r_q P_{dc-q} \quad (4)$$

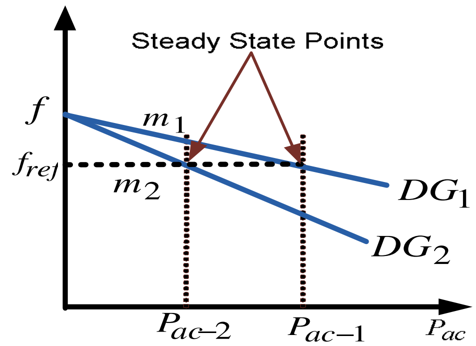

Fig. 2. Droop Characteristics of ac HPS.

$$r_q = \frac{V_{dc}^{min} - V_{dc}^{max}}{P_{dc-q}^{max}} \quad (5)$$

$$r = -\frac{1}{k_{Pdc}} = \frac{-\Delta P_{dc}}{\Delta V_{dc}} = -\frac{P_{dc}}{V_{dc\,max} - V_{dc}} \quad (6)$$

In (4), V_{dc-q} is the output voltage, V_{dc}^{ref} is the reference voltage at no load, P_{dc-q} is the generated active power and r_q is droop slope in the q^{th} dc source. Droop characteristic in each source is chosen inversely proportional to its capacity in dc droop as similar to ac droop.

Here k_{Pac} and k_{Pdc} are the slopes of droop characteristic of DGs that participate in active power adjustments in the ac and dc HPS, respectively. f_{max} and V_{dcmax} are maximum frequency and maximum dc voltage of ac and dc HPS respectively.

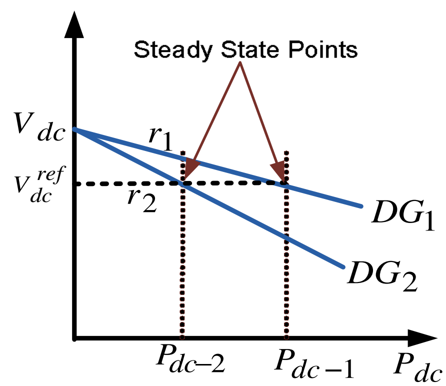

Fig. 3. Droop characteristics of dc HPS.

The downside of the conventional droop control techniques are:

(i) The droop equations are valid only for inductive transmission lines. They are unsuccessful for low voltage distribution networks which are highly resistive.

(ii) Poor voltage regulation of critical loads with the application of reactive power control.

(iii) It is inappropriate for nonlinear and single-phase loads as the harmonic current sharing is not taken into account.

(iv) It is prone to load dependent frequency deviation.

B. Improved Droop

The improved droop control methods are applicable for low voltage resistive distribution lines [31]. In this method, the inverter output voltage magnitude is reduced in reference to increase in active power output, while frequency is increased with a corresponding increase in reactive power output. The active power and reactive power in improved droop are given by (7) and (8) respectively.

$$P = \frac{VE - V^2}{R} \qquad (7)$$

$$Q = \frac{-VE}{R}\delta \qquad (8)$$

where V and E are DG output voltage and common ac bus voltage respectively. P-V droop and Q-ω characteristics are represented by (9) and (10) respectively

$$V_i = V_0 - m_p P \qquad (9)$$

$$\omega_i = \omega_0 + n_p Q \qquad (10)$$

$$m_p = \frac{\Delta E}{P_{max}} \qquad (11)$$

$$n_p = \frac{\Delta\omega}{2Q_{max}} \qquad (12)$$

where ω_0 and V_0 are the angular frequency and DG output voltage references values, m_p and n_p are droop coefficients for the P-V droop and Q-ω characteristics.

This method considerably improves power-sharing in low voltage ac resistive lines, but it depends on system parameters and is incompatible for nonlinear loads.

C. Angle Droop Control

Angle droop control has significantly low-frequency deviation as compared to other droop control [32]. In this method phase angle measurements of the output voltage of the converter can be used from low bandwidth communication techniques. In this method it is assumed that an inductive impedance exist between the converter and ac bus. The angle droop equations are expressed as:

$$\delta_i = \delta_{rat} - m_p(P_i - P_{rat}) \qquad (13)$$

$$V_i = V_{rat} - n_p(Q_i - Q_{rat}) \qquad (14)$$

Where δ_i and δ_{rat} are converter output voltage angle and rated converter output voltage angle respectively. V_i and V_{rat} are converter output voltage and rated converter output voltage respectively. P_i and Q_i are active and reactive power output of the converter respectively; P_{rat} and Q_{rat} are rated active and reactive power output of the converter respectively; and m_p and n_p are droop coefficients.

D. Virtual Resistance based Droop Control

In this control strategy to achieve power sharing, effect of line resistances is considered [33]. To overcome the effect of line resistance, a virtual resistance, R_v, is considered in the feedback path and the output voltage equation can be expressed as given in (15).

$$V_0^* = V_{ref} + \delta V_0 - R_v i_0 \qquad (15)$$

δV_o is the compensator output required for restoring the HPS voltage. i_o is the output current, R_v is the output impedance, and V_{ref} is the output voltage reference at no load.

E. Normalized Combined Droop Control

In contrast to frequency, voltage is not a global parameter in a power system. In other words, different bus voltages in a typical power system are not same due to line impedance and grid topology. Disproportionate bus voltages in dc side and disproportionate frequency in ac side will result in uneven per-unit active power participation of sources. Normalization of frequency and voltage is used to calculate the power references in this method [34, 35]. Power sharing among sources in an ac HPS can be realized by the droop control method whose *P–f* expression for the p^{th} DG unit can be expressed as

$$f = f^{ref} + m_p P_{ac-p} \qquad (16)$$

$$m_p = \frac{f_{min} - f_{max}}{P_{ac-p}^{max}} \qquad (17)$$

Power sharing among *p* sources in ac HPS can be obtained as

$$\frac{P_{ac-1}}{P_{ac-1}^{max}} = \frac{P_{ac-2}}{P_{ac-2}^{max}} \ldots\ldots \frac{P_{ac-p}}{P_{ac-p}^{max}} \qquad (18)$$

From the literature it is observed that conventional droop control is effective under variations in load. The power in the interlinking converter is equal and opposite of each other. The control strategy has two loops, inner and outer loop; the function of inner loop is to mainly control the output voltage v_0 to track the reference generated by outer loop. The *P-f* droop is used to generate the reference values acquired by inner loop.

Fig. 4 shows the droop characteristics for ac HPS. The sudden increase in load on HPS_1, results in the reduction of HPS_1 frequency. To compensate the load disturbance in HPS_1, power from HPS_2 is transferred to HPS_1 through IPC. The droop characteristic of q^{th} DG in dc HPS is given by

$$V_{dc-q} = V_{dc}^{ref} + r_q P_{dc-q} \qquad (19)$$

$$r_q = \frac{V_{dc}^{min} - V_{dc}^{max}}{P_{dc-q}^{max}} \qquad (20)$$

Fig. 5 describes basic droop characteristics and operating point with respect to change in power of dc HPS.

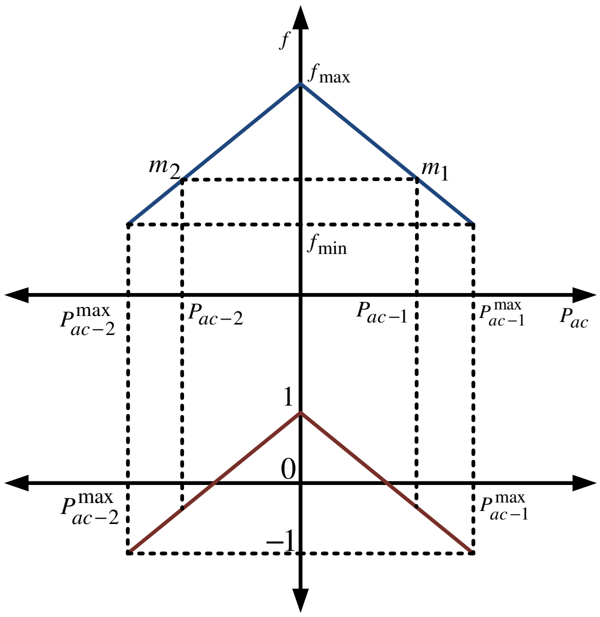

Fig. 4. Normalized droop characteristics of ac HPS.

The power sharing among sources in *dc HPS* is given by the following equation where sources share the load in proportion to their maximum power available.

$$\frac{P_{dc-1}}{P_{dc-1}^{max}} = \frac{P_{dc-1}}{P_{dc-2}^{max}} \ldots\ldots\ldots = \frac{P_{dc-q}}{P_{dc-q}^{max}} \tag{21}$$

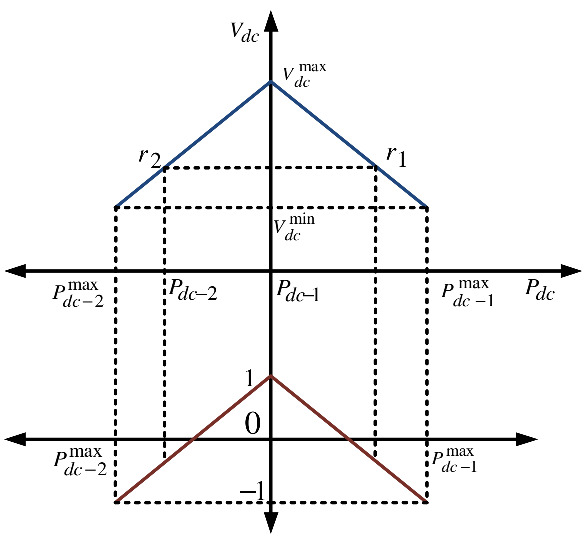

Fig. 5. Normalized droop characteristics of dc HPS.

To achieve proper power sharing in separate ac and dc droop characteristics are normalized and combined to determine the power flow on the IPC.

The normalization of voltage and frequency for intertied HPS is shown in Fig. 6. The combined ac-dc droop characteristics given by

$$f = f^{ref} + M\sum_{p=1}^{x} P_{ac-p} \tag{22}$$

Where combined ac droop coefficient is given by

$$M = \frac{1}{\sum_{p=1}^{x} \frac{1}{m_p}} \tag{23}$$

The combined dc droop characteristics represented as

$$V_{dc} = V_{dc}^{ref} + R\sum_{q=1}^{y} P_{dc-q} \tag{24}$$

Where combined ac droop coefficient is given by

$$R = \frac{1}{\sum_{q=1}^{y} \frac{1}{r_q}} \tag{25}$$

$$f' = 1 + \frac{M}{0.5(f_{max} - f_{min})}\sum_{p=1}^{x} P_{ac-p}$$
$$V_{dc}' = 1 + \frac{R}{0.5(V_{dc}^{max} - V_{dc}^{min})}\sum_{q=1}^{y} P_{dc-q} \tag{26}$$

The combined ac-dc droop characteristics have same dimensions on x and y-axes as shown in Fig. 6. Here PI controller is engaged to exchange power between ac and dc HPS to equalize f' and V_{dc}

$$P_{ac-ipc} = P_{dc-ipc} = (k_p + \frac{k_i}{s})(f' - V_{dc}') \tag{27}$$

Where k_p and k_i are controller gains, and $P_{ac\text{-}ipc}$ and $P_{dc\text{-}ipc}$ are power flows in IPC_{ac} and IPC_{dc}. In case of no power exchange from storage HPS, $P_{ac\text{-}ipc} = P_{dc\text{-}ipc}$. By enforcing $f' = v_{dc}'$, it can be deduced that

$$\frac{\sum_{p=1}^{x} P_{ac-p}}{\sum_{p=1}^{x} P_{ac-p}^{max}} = \frac{\sum_{q=1}^{y} P_{dc-q}}{\sum_{q=1}^{y} P_{dc-q}^{max}} \tag{28}$$

It is evident from above equation that all sources in ac and dc *HPS* share the power according to their power ratings.

F. Highlights of Control Techniques

Some highlights of the control aspects in intertied HPS are presented here.

(i) DC HPS in comparison to ac HPS or intertied HPS does not require active power-frequency droop control.

(ii) The control is more complicated in stand-alone mode of intertied HPS; due to the absence of a global variable which can be used for power-sharing, voltage and frequency regulation.

(iii) The specified droop control should be independent of line impedance between the inverter and common ac/dc bus for proper load sharing among the ac and dc sources.
(iv) An additional interlinking power converter between ac and dc HPS plays a key role in power balancing in both the HPS in grid-connected as well as in standalone mode of operation.
(v) Various droop control results in achieving different level of power sharing and voltage and frequency regulation at different levels
(vi) By comparing results achieved from different droop methods; normalized combined droop method achieves proper power sharing in ac and dc HPS.

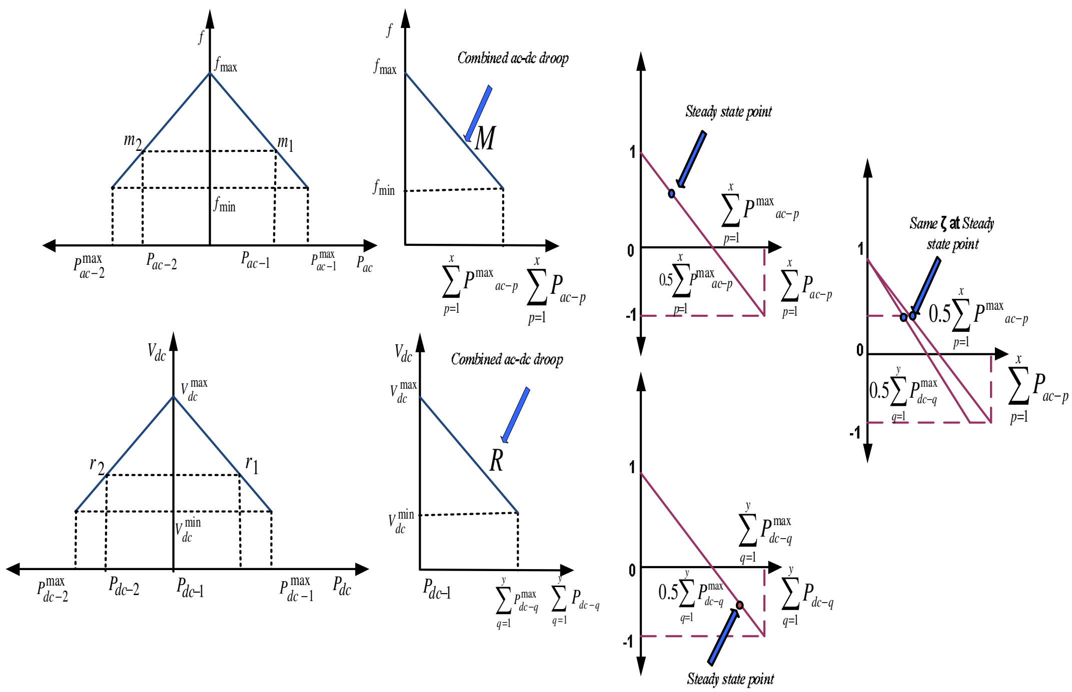

Fig. 6. Combined ac-dc droop characteristics.

IV. CONCLUSIONS

This paper reports a systematic literature review of control aspects in intertied HPS. There has been a lot of research on the various aspects of the intertied HPS. The control aspects of intertied hybrid power system are the most studied topics of interest. Without a stable and accurate control, the intertied HPS implementation is not feasible. Although ac HPS has been a widely researched topic, dc and intertied ac-dc HPS are gradually gaining interest of the researchers from the perspective of reliability, minimization of converter-losses and efficiency. In case of centralized control if the central controller fails in its operation due to the communication error, whole system may malfunction. However, in case of decentralized control, there is no need of communication lines among different controllers thereby system cost reduced and chance of single point failure is decreased. The decentralized control is less reliable than the centralized one, as the local controllers cannot function optimally due to lack of information about the system operating state. This drawback can be overcome by using a distributed control approach, where the local controllers interact with each other within intertied HPS.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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How to cite this article: Gupta, P. and Swarnkar, P. (2019). Review of Control Techniques in Intertied AC- DC Hybrid Power System**.** *International Journal on Emerging Technologies*, **10**(2): 08-14.