Cost Based Dynamic Load Dispatch for an Autonomous Parallel Converter Hybrid AC-DC Microgrid

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***Abstract*—Design of a robust controller for dynamic load sharing is one of the major challenges in microgrid operation. Conventional droop controller based dynamic load dispatch schemes are discussed in literatures, which facilitates load sharing among different generators in proportion to their generation capabilities. However, not only the generation capacity, but also, the generation cost plays an important role while deciding load sharing among different distributed energy sources (DER's) in a microgrid system. This paper presents mathematical modeling, analysis and simulation results for a novel droop controller based dynamic load dispatch scheme, which includes cost, in addition to generation capacity, as a governing parameter for dynamic load sharing in a parallel converter hybrid AC-DC microgrid system. The results are demonstrated on a simple microgrid structure consisting of a solar photovoltaic and wind turbine generation system alongwith a composite load.**

I. Introduction

With increasing penetration of renewable energy sources in conventional distribution network, a number of challenges are to be addressed by power engineers, researchers and policy makers. Designing a suitable architecture, handling power quality issues, simultaneous operation of multiple solid state converters, communication between various sources, stability issues and economic concerns are main challenges cited in literature [1]. AC, DC and AC-DC hybrid microgrid are three major architectures that have been developed and analyzed so far to deal with these challenges [2]–[5]. An AC microgrid consists of an AC bus and all sources with DC output are connected to AC bus through DC/AC converter. Similarly, DC microgrid consists only DC bus in the network. An AC-DC hybrid microgrid includes both AC and DC bus in the network and present the advantages of both AC and DC microgrid based architectures.

Not only with the required control strategy, dynamic power exchange between AC and DC bus can be handled, but a suitable control scheme is necessary to handle the intermittent nature of renewable energy sources. Under dynamics of varying load demand and fluctuating power generation, a robust control technique is required to take care of power sharing among different distributed energy sources. Droop control is a popular technique discussed in literatures that is used for power sharing among synchronous generators in conventional power plant [1], [3], [6]. Same droop control technique has also been used in various microgrid architectures for power sharing between different energy sources. The active power-frequency droop characteristics of different generators is used for power sharing in proportion of their generation capabilities [7].

Efficiency of one renewable source varies from other with different converter topology requirements. For example, solar PV system is connected with DC/AC converter, while doubly fed induction generator based wind energy conversion system requires AC/DC/AC converter. Efficiency of converters of different topologies also varies as they have different number of switches and different switching schemes [8]. So the cost becomes an important parameter, while deciding power sharing among different sources in a microgrid.

In this work, a modified cost based droop controller for parallel converter AC-DC microgrid is proposed . Section II presents dynamic model of AC-DC hybrid microgrid. Section III presents the mathematical modeling of renewable energy sources cost function and cost based droop controller. Simulation and results are presented in section IV. Conclusion follows next.

II. Dynamic Model of AC-DC Hybrid Microgrid

Fig. 1 presents the electrical equivalent circuit of hybrid microgrid for which the droop controller is developed. DC bus 1 and 2 are connected to their respective DC sources V_{dc1} and V_{dc2}. The DC buses are connected to AC bus through two parallel converters 1 and 2 via respective transmission lines. Each of the AC bus is connected to a composite load consisting a linear R-L load and a constant power type load.

Dynamic equations of transmission line, linear load and

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constant power type load in d-q frame is given in eq (1-4).

$$pI_{siq} = \frac{1}{L_{si}}(M_{qi}\frac{V_{dci}}{2} - V_{qmi} - R_{si}I_{siq} - L_{si}\omega_{si}I_{sid}) \quad (1)$$

$$pI_{sid} = \frac{1}{L_{si}}(M_{di}\frac{V_{dci}}{2} - V_{dmi} - R_{si}I_{sid} + L_{si}\omega_{si}I_{siq}) \quad (2)$$

$$pI_{Liq} = \frac{1}{L_{Li}}(V_{qmi} - R_{Li}I_{Liq} - L_{Li}\omega_{si}I_{Lid}) \quad (3)$$

$$pI_{Lid} = \frac{1}{L_{Li}}(V_{dmi} - R_{Li}I_{Lid} + L_{Li}\omega_{si}I_{Liq}) \quad (4)$$

Where M_{di} and M_{qi} are d and q axis modulation index of parallel converters. i represents the number of subsystem, p denotes differential operator d/dt. Modulation indices M_{di} and M_{qi} for parallel converters are obtained with the help of signals from Phase Locked Loop (PLL). PLL measures instantaneous voltage angle of load bus and respective converters. The equations for M_{di} and M_{qi} are given in (5-6).

$$M_{qi} = M_i cos((\theta_i - \theta_{si}) + (\theta_{i0} - \theta_{si0}) \quad (5)$$

$$M_{di} = -M_i sin((\theta_i - \theta_{si}) + (\theta_{i0} - \theta_{si0}) \quad (6)$$

Where θ_{i0} and θ_{sio} are initial values of converter angle and system angle respectively. M_i is the modulation index of respective converters. Power supplied by two converters is calculated in terms of AC bus voltage and transmission line current. Equations (7-8) present the expression for active and reactive power supplied by converters,

$$P_{si} = \frac{3}{2}(V_{qmi}I_{qsi} + V_{dmi}I_{dsi}) \quad (7)$$

$$Q_{si} = \frac{3}{2}(V_{qmi}I_{dsi} - V_{dmi}I_{qsi}) \quad (8)$$

As a signal processing unit, PLL is designed and connected at each AC bus to measure the respective instantaneous frequency. Based on measured frequency, PLL generates a reference frequency signal as controlling signal for converters after comparing output of load bus and converters. Dynamic equation for PLL is given as follows,

$$\frac{\theta_{si}}{\theta_i} = \frac{pV_{mi}K_{Ppll} + V_{mi}K_{Ipll}}{p^2 + pV_{mi}K_{Ppll} + V_{mi}K_{Ipll}} \quad (9)$$

Where θ_{si} and θ_i are instantaneous measured angle of system and converter respectively. K_{Ppll} and K_{Ipll} are constants for PI controller that generates error signal.

III. Generation Cost Function for Renewable Energy Sources

Generation cost of any energy source is actually a function of instantaneous generated power of that individual source. The overall cost function of a conventional generator depends upon a number of factors that include maintenance cost, fuel operating cost and emission penalty. Cost function which includes all these factors is a sum of individual costs presented in (10),

$$C_{P,i}(P_i) = C_{P,m,i}(P_i) + C_{P,f,i}(P_i) + C_{P,e,i}(P_i) \quad (10)$$

Where $C_{P,i}(P_i)$ is total active power generation cost of i^{th} generator, $C_{P,m,i}(P_i)$ is maintenance cost, $C_{P,f,i}(P_i)$ is

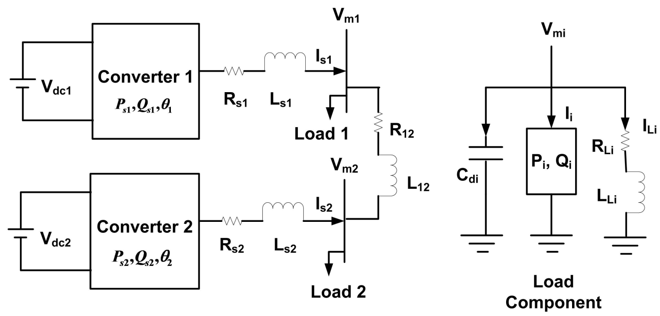

Fig. 1. AC-DC hybrid microgrid structure

fuel cost and $C_{P,e,i}(P_i)$ is emission penalty for concerned generator. Individual cost functions for maintenance, fuel cost and emission penalty is given as below,

$$C_{P,m,i}(P_i) = K_{m,i}P_i \quad (11)$$

$$C_{P,f,i}(P_i) = K_{f,i}(a_i + b_iP_i + c_iP_i^2) \quad (12)$$

$$C_{P,e,i}(P_i) = K_{emm,i}(\alpha_i + \beta_iP_i + \gamma_iP_i^2 + \epsilon_i exp(\rho_i)P_i) \quad (13)$$

$K_{m,i}$, $K_{f,i}$, a_i, b_i, c_i, $K_{emm,i}$, α_i, β_i, γ_i, ϵ_i, ρ_i all are coefficients that characterize the cost of i^{th} generator.

Unlike conventional generators, non-conventional or renewable energy sources like solar, wind, fuel cell etc. are often connected to AC bus through solid state converters. Efficiency of these converters at low load condition becomes quiet significant. In order to include high converter losses into cost function as cost penalty, generator power is modified as follows,

$$P_i = \eta_i(P_i + P_{losses}) \quad (14)$$

$$P_i = \eta_i(P_i + K_{l,i}(v_i + u_iP_i + w_iP_i^2)) \quad (15)$$

Where η_i is efficiency of converter associated with i^{th} renewable energy source in a microgrid system, $K_{l,i}$, v_i, u_i and w_i are coefficients that characterize cost of specific energy source. A final expression for cost function of renewable energy sources that includes direct cost as well as converter loss efficiency is given below,

$$C_{P,i}(P_i) = K_{o,i}(P_i + K_{l,i}(v_i + u_iP_i + w_iP_i^2)) \quad (16)$$

$$K_{o,i} = \eta_i(K_{m,i} + K_{f,i} + K_{emm,i}) \quad (17)$$

Power electronic converter attached with DER maintain the output of associated generator at desired magnitude and frequency through proper control. In addition to this, it also take care of reactive power demand from load side. Due to this reason, converter's are rated in kVA unit. To include the cost associated with reactive power generation, a reactive power generation cost function is proposed in literature. One of the proposed method is that reactive power cost is presented through active power loss as a percentage of reactive power. The expression for reactive power generation cost is given below,

$$C_{Q,i}(Q_i) = C_{P,i}(P_i + \nu Q_i) - C_{P,i}(P_i) \quad (18)$$

In above expression, ν presents the fraction of reactive power represented as active power loss. This value is normally stated as 3-5 percent of reactive power for synchronous generator and inverters.

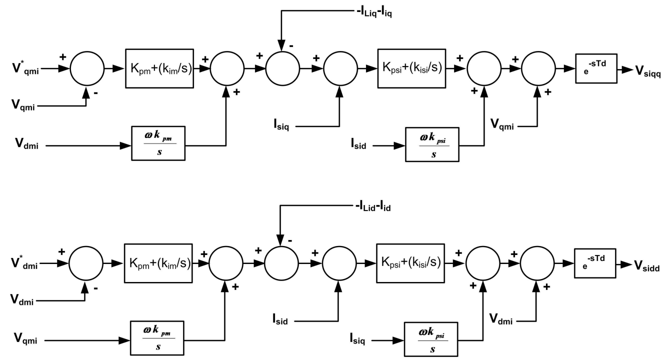

Fig. 2. Modified droop control scheme

IV. Modified Droop Controller Based on Generation Cost Functions

Droop control technique is one of the most popular techniques in conventional power plants. In power stations, where multiple generators operate simultaneously, droop control scheme is used for sharing total load among generators in a certain proportion. In this scheme, active power-frequency droop characteristics of generators is used to calculate the share of active power generation of individual generator to satisfy the total load on power station. Similarly, reactive power-voltage droop characteristics of generators is used to determine reactive power share of an individual generator. Mathematical representation of conventional droop control is given below,

$$\theta_i = \frac{1}{p}(\omega_n - m_{p,i}P_{si}) \tag{19}$$

$$V_{mi} = V_n - n_{q,i}Q_{si} \tag{20}$$

Where ω_n and V_n are rated frequency and rated voltage of i^{th} bus. $m_{p,i}$ and $n_{q,i}$ are active power and reactive power droop coefficients respectively. Instantaneous active and reactive powers of individual generators are calculated from d-q axis voltage and currents as given below,

$$P_{si} = \frac{3}{2}(V_{qmi}I_{qsi} + V_{dmi}I_{dsi}) \tag{21}$$

$$Q_{si} = \frac{3}{2}(V_{qmi}I_{dsi} - V_{dmi}I_{qsi}) \tag{22}$$

Power sharing in conventional droop scheme is completely dependent on active and reactive power of individual generators. It does not include cost as any parameter which is actually an important parameter while dealing with renewable energy sources.To include the cost as controlling parameter, a cost based droop controller is proposed which calculates the power sharing of generators in terms of cost functions.

In a microgrid system, different generators can be of different rated capacities. This is a reason why running cost consideration goes wrong as generators of different capacities will lead to misleading cost values. In order to remove this miscalculation, cost functions are translated into per unit based on their generation capabilities as given below,

$$C'_{P,i}(P_i) = \frac{C_{P,i}(P_i)}{P_{i,max}} \tag{23}$$

Where $P_{i,max}$ is the maximum power that i^{th} generator can generate.

An important consideration is that cost function of generators also include the no load operation cost. However, for the purpose of droop control, a running cost alone is required so that proper power sharing could be done. To exclude the no load cost from cost function, following modification is applied in the cost function,

$$C''_{P,i}(P_i) = C'_{P_i}(P_i) - C'_{P,i}(P_i = 0) \tag{24}$$

Finally, the conventional droop control scheme is modified to incorporate the cost function as governing parameter of the control strategy. Droop coefficients for active and reactive power droop characteristics is obtained as follows,

$$m_{p,i,c} = \frac{\omega_n - \omega_{n,min}}{C''_{P,max}} \tag{25}$$

$$n_{q,i,c} = \frac{V_n - V_{n,min}}{C''_{Q,max}} \tag{26}$$

Where $m_{p,i,c}$ and $n_{q,i,c}$ are active and reactive power droop coefficients with cost as governing parameter, $\omega_{n,min}$ and $V_{n,min}$ are minimum values allowed for frequency and voltage while operating with droop controller. Different types of generators in microgrid will have different cost functions. To develop a uniform droop coefficients for all the generators, $C''_{P,max}$ and $C''_{Q,max}$ are included in control technique. These are the maximum value among cost function values of all generators at full load and is represented as,

$$C''_{P,max} = max\{C''_{P,i}(P_{i,max})\}_{i=1,...i} \tag{27}$$

$$C''_{Q,max} = max\{C''_{Q,i}(Q_{i,max})\}_{i=1,...i} \tag{28}$$

Based on new droop coefficients, reference bus angle and bus voltage is calculated as follows,

$$\theta_{i,c} = \frac{1}{p}(\omega_n - m_{p,i,c}C''_{P,i}(P_i)) \tag{29}$$

$$V_{m,i,c} = V_n - n_{q,i,c}C''_{Q,i}(Q,i) \tag{30}$$

Figure 2 presents the schematic diagram of cost based droop control scheme used in this paper.

V. Simulation and Results

Performance of cost based droop controller implemented with microgrid system is tested under varying load conditions. Data given in table I presents the system and controller parameters. A Constant P-Q type load is varied during simulation time of 2.5 sec and response of both of the converters under

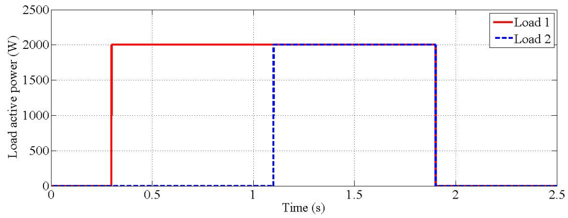

Fig. 3. Active Power components of constant power type load

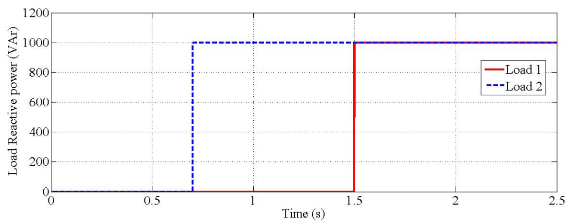

Fig. 4. Reactive power components of constant power type load

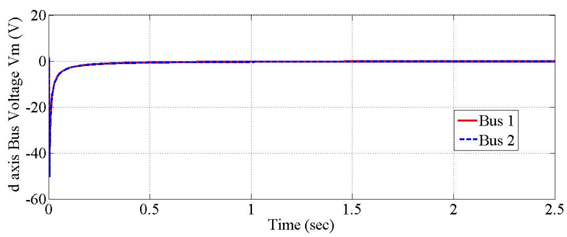

Fig. 5. d Axis component of load bus voltage

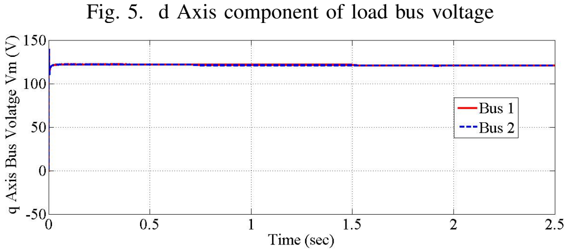

Fig. 6. q axis component of load bus voltage

varying condition is plotted against time. Fig 3-4 presents active and reactive load components of constant power loads connected at bus 1 and bus 2. A constant load of 2000 W is available on bus 1 during 0.3-1.9 sec. Similarly a load of 2000 W is available at bus 2 during 1.1-1.9 sec. As the load demand on buses 1 and 2 varies, bus voltages and their respective angles fluctuate. The instantaneous voltage and angle is measured by Phase Locked Loop (PLL) and a reference signal for converter control is obtained. Principle of operation of PLL is that it aligns measured voltage to q axis and sets d axis voltage component as zero. Measurement corresponding to d axis voltage and q axis voltage for bus 1 and 2 is given in fig. 5-6. Based on measurement from PLL, instantaneous active and reactive power is calculated by controller developed in this paper.

Cost based droop controller obtains corresponding frequency for both load buses connected with renewable energy sources. Fig 7 gives the bus frequencies calculated in rad/sec. A PI controller based droop control scheme generates d and

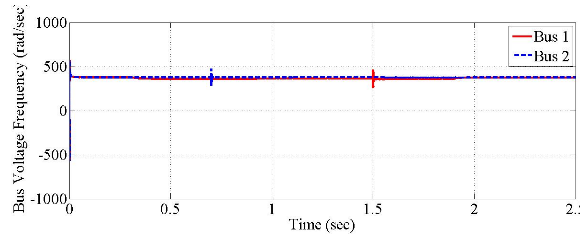

Fig. 7. AC bus voltage frequency

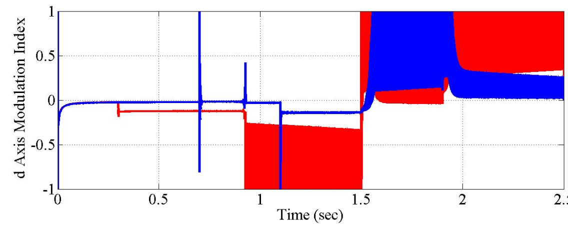

Fig. 8. d axis modulation index

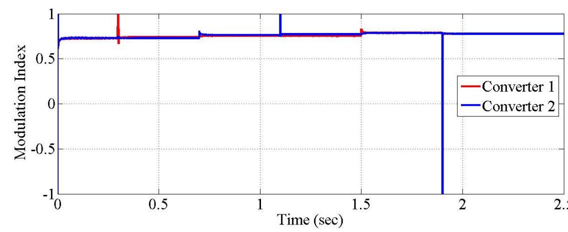

Fig. 9. q axis modulation index

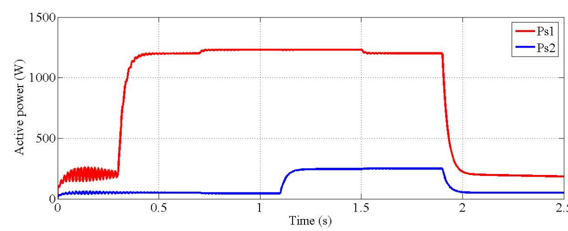

Fig. 10. Active power sharing between two converters

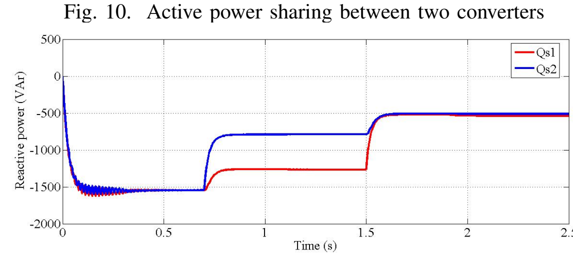

Fig. 11. Reactive power sharing between two converters

q axis modulation index component for both of the converters which maintains the bus voltage constant. Modulation index for converter 1 and converter 2 in d and q axis is given in fig 8-9. Based on obtained modulation index, converters operate and maintain the desired power sharing as guided by cost based droop controller. Variation of active and reactive power sharing of two sources with variation of load demand is given in fig 10-11.

In conventional droop controller scheme, power sharing

TABLE I
PARAMETERS OF DERS AND DROOP CONTROLLER

Parameters	Values	Parameters	Values
V_n	120 V	$K_{P,pll}$	4.44
ω_n	377 rad/sec	$K_{I,pll}$	1184
R_{si}	0.1 Ω	$K_{P,mi}$	0.628
L_{si}	4×10^{-3} H	$K_{I,mi}$	0
R_{12}	0.04 Ω	$K_{P,si}$	25.13
L_{12}	1×10^{-3} H	$K_{I,si}$	628.32
C_{di}	$200 \times \times 10^{-6}$ F	$C''_{P,1}(P_{1,max})$	0.246
R_{Li}	$10 \times 10^3 \Omega$	$C''_{P,2}(P_{2,max})$	0.047
L_{Li}	$10 \times 10^3 H$	$C''_{Q,1}(Q_{1,max})$	0.01212
$P_1 = P_2$	1000 W	$C''_{Q,2}(Q_{2,max})$	0.01818
$Q_1 = Q_2$	1000 VAr	$m_{p,i,c}$	8.13
$V_{m1} = V_{m2}$	150 V	$n_{q,i,c}$	8.25

among parallel generators is done in proportion of their generating capabilities. Under cost based droop controller scheme presented in this paper, power sharing ratio among two parallel converters is 0.2 which is equal to the ratio of cost coefficients of two renewable sources taken in this study. This clearly indicates that power sharing among two generators is in proportion to the cost functions. Similarly for reactive power sharing, the ratio of reactive power supplied by two converters is 1.5 which is equal to the ratio of reactive power generation cost coefficients of two parallel generators. Hence the results validate that the cost based droop controller facilitates power sharing in proportion of cost functions.

CONCLUSION

A cost based droop controller scheme for dynamic load dispatch is presented in this paper. The proposed scheme successfully facilitates cost function based droop controller for power sharing among the generators in a parallel converter AC-DC hybrid microgrid. Mathematical modeling of hybrid microgrid and generation cost functions for renewable energy sources is presented in this work. A conventional droop controller is extended to include cost as a governing parameter for power sharing. Controller is made to operate under varying load condition. Since cost function coefficients for active and reactive powers have been obtained at full load conditions, so the power sharing according to proposed scheme is based on both generation capability as well as cost functions. Simulation results conclude that dynamic power sharing among generators in proportion to generation cost and generation capacity is achieved through proposed controller.

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