A Novel Approach for Active and Reactive Power Sharing in Microgrids

Kartheek Vankadara[1], K.Jagadeesh Kumar[2]
[1]Assistant Professor, Department of E.E.E., Shree Institute of Technical Education, Tirupati, A.P., India.
[2]Assistant Professor, Department of E.E.E., Shree Institute of Technical Education, Tirupati, A.P., India.

ABSTRACT: The parallel action of inverters in microgrids is supported on droop process. The actual droop process comprises of rectifying the final voltage frequency and size to obtain self-standing power sharing without control wire interconnections. The actual voltage droop process reveals several drawbacks such as interior multiloop feedback control, frequency and voltage deviations. This paper intends a modern control tactic in microgrid applications by bringing down the substantial flux in place of the inverter final voltage. Firstly, the substantial flux and the active and reactive powers are mathematically obtained and a relationship is established between them which are employed to promote a modern flux droop technique. A small signal model is improved in direction to sketch the main control parameters and to study the steadiness as well as the system dynamics. A direct flux control step by step technique is used to adjust the substantial flux agreeing to the droop controller to evade the utility of PI controllers and PWM modulators. The simulation output shows that intended flux droop tactic can obtain active and reactive power sharing by decreasing the frequency deviation than the actual droop process, thus spotlights the influential usage in microgrid applications.
KEYWORDS: Sharing of active and reactive power; flux droop; microgrids; power quality.

I. INTRODUCTION

A MICROGRID is a group of microgenerators united to the territorial low-voltage mesh through power electronic converters. Compared to individual distributed generation (DG) one, microgrids propose many technical benefits in terms of control flexibility and the ability to embody renewable energy sources [1]-[3]. However, power quality and system stableness are serious issues due to the alternating character of the renewable energy sources and the fluctuating load outline. In addition, as the sharpness and the DG units grow, the power converters are directed to act more effectively and powerfully to support maximum power quality and dynamic stability. Modern and professional control techniques are necessary to meet the essentials.

The actual droop process has several disadvantages such as complex interior multiloop feedback control, frequency and voltage distortions. To exhibit the mentioned voltage from the droop controller, a multiloop feedback control plan is commonly used to control the inverters. In the multiloop feedback control, PI regulators are employed external voltage loop and interior current loop. Modulation such as sinusoidal PWM is needed to produce the ultimate gate drive signals. As an effect, this process needs complicated coordinate change, and much tuning attempt is required to insure the system stableness, which causes it difficult to fulfill. It is well understood that excellent power sharing is obtained when employing the actual droop process, but this leads to declination of the voltage regulation due to the frequency and the magnitude of the inverter output voltage which are governed instantly. The voltage distortion could be disagreeable in applications where the main problem is with power quality.

In modern years, much study has been done to correct the voltage droop process so as to gain more dynamic and steadiness of the system. For example, to obtain more transient response, the derivative-integral terms were introduced into the droop controller. By decoupling the real and reactive powers, a virtual frame transformation or impedance method was presented for better power sharing. To improve the power quality, an angle controller is introduced by bringing down the inverter final voltage in the place of frequency. The disadvantage is that other inverter phase angles are not assumed. To procure synchronization, GPS signal is being employed [5]. As to counterbalance for the voltage distortion caused by droop characteristics, a multilayer control strategy was presented [6]. The above-mentioned methods are improved with the help of voltage droop method; by using P-ω and Q-V relationships. So, difficult multiloop feedback loops are unpreventable; useful power sharing is obtained at the cost of voltage deviation.

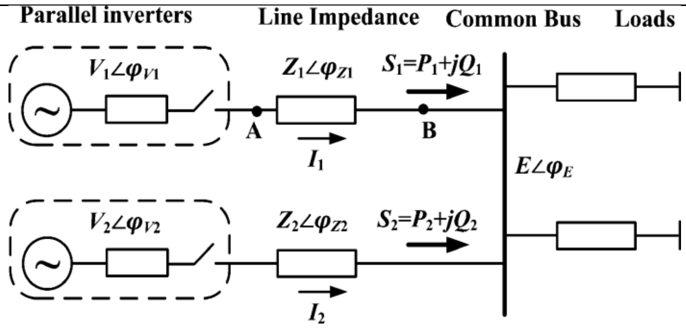

Fig. 1. Two parallel connected inverters in microgrids equivalent circuit.

Recently a new virtual flux droop method was designed which can obtain similar self-governing power sharing to accepted voltage droop control, but the frequency deviation is very low [7]. The control configuration is very simple and no multiloop feedback controls; due to which PI controllers are evaded and PWM modulators are removed. The theory is further improved and the new tactic is implemented and simulated. The relationship between the power flow and inverter flux is deduced which is used to project a new virtual flux droop method in section II. The small signal plan is improved which helps in calculating the control parameters and studies stability of the system in section III. A Direct Flux Control (DFC) scheme is conferred in section IV which restricts the inverter in order to exhibit the demanded virtual flux. The complete control strategy of the microgrid is discussed by embodying the intended virtual flux droop method with the Direct Flux Control scheme in section V. The virtue of the intended strategy is projected using MATLAB/SIMULINK in section VI.

II. PROPOSED DROOP METHOD

Two distributed generator units connected to an AC bus through their inverters are shown in figure 1. The system equivalent circuit is described by the mathematical equations which are given by

$$V = RI + L\frac{dI}{dt} + E \qquad (1)$$

$$S = P + jQ = I^{*}E \qquad (2)$$

where I, V and E are line current vector, inverter voltage vector and common AC bus voltage vector respectively. The impedance of the transmission line is given by Z where Z=(R+jωL). P and Q are real and reactive powers flowing from distributed generator to common AC bus and complex conjugate is denoted by *. The vectors of virtual flux at nodes A and B are given below in the fashion of flux definition as in an electrical machine.

$$\psi_V = \int_{-\infty}^{t} V d\tau \qquad (3)$$

$$\psi_E = \int_{-\infty}^{t} E d\tau \qquad (4)$$

The vectors of converter flux at junction A and of AC-bus virtual flux at junction B from (3) and (4) are represented as

$$\varphi_{fV} = \varphi_V - \frac{\pi}{2}, |\psi_V| = \frac{|V|}{\omega} \qquad (5)$$

$$\varphi_{fE} = \varphi_E - \frac{\pi}{2}, |\psi_E| = \frac{|E|}{\omega} \qquad (6)$$

where φ_E and φ_V are the phase angles of E and V; φ_{fE} and φ_{fV} are the phase angles of φ_E and φ_V. ω is the angular frequency of the voltages. Practically R, line resistance is not considered as the impedance of the line is highly inductive. Combining (1), (3) and (4) gives

$$I = \frac{1}{L}(\psi_V - \psi_E) \qquad (7)$$

The apparent power is obtained when substituting (7) into (2) which is given as

$$S = \frac{1}{L}(\psi_V - \psi_E)^{*} E \qquad (8)$$

Also, into (8), substituting (5) and (6) yields

$$S=\frac{1}{L}\left(|\psi_V|e^{j\left(\varphi_V-\frac{\pi}{2}\right)}-|\psi_E|e^{j\left(\varphi_E-\frac{\pi}{2}\right)}\right)^{*}\omega|\psi_E|e^{j\varphi_E} \quad (9)$$

$$S=\frac{\omega}{L}\left(|\psi_E||\psi_V|e^{j\left(\frac{\pi}{2}+\varphi_E-\varphi_V\right)}-|\psi_E|^2 e^{j\left(\frac{\pi}{2}+\varphi_E-\varphi_E\right)}\right) \quad (10)$$

So, volt-amps flowing from the distributed generation unit to common AC bus is derived from (10) which yields

$$S=\frac{\omega}{L}\left[|\psi_E||\psi_V|\sin(\psi_V-\psi_E)+j\left(|\psi_E||\psi_V|\cos(\psi_V-\psi_E)-|\psi_E|^2\right)\right] \quad (11)$$

The real and reactive power is obtained by splitting (11) into real and imaginary which yields

$$P=\frac{\omega}{L}|\psi_E||\psi_V|\sin\delta \quad (12)$$

$$Q=\frac{\omega}{L}\left(|\psi_E||\psi_V|\cos\delta-|\psi_E|^2\right) \quad (13)$$

where $\delta=\varphi_V-\varphi_E=\varphi_{fV}-\varphi_{fE}$. As the angular difference is very small, so it is assumed as sin (δ) =δ and cos(δ) = 1 which yields

$$P=\frac{\omega}{L}|\psi_E||\psi_V|\delta \quad (14)$$

$$Q=\frac{\omega|\psi_E|}{L}\left(|\psi_V|-|\psi_E|\right) \quad (15)$$

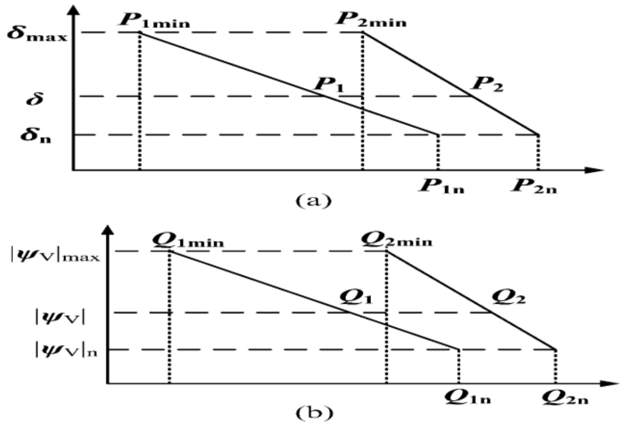

Fig. 2. Real and reactive power sharing with the new flux droop method. (a) P-δ characteristic (b) Q-$|\psi_V|$ characteristic.

So, the real power is directly proportional to difference of flux phase angle δ and reactive power is proportional to the difference of magnitude of the flux ($|\psi_V|-|\psi_E|$). Depending on the analysis mentioned, by bringing down the inverter virtual flux a new method is been proposed here which yields

$$\delta=\delta_n-m(P_n-P) \quad (16)$$

$$|\psi_V|=|\psi_V|_n-n(Q_n-Q) \quad (17)$$

where δ_n is difference of nominal phase angle between ψ_V and ψ_E and $|\psi_V|_n$ is inverter flux nominal amplitude. P_n and Q_n are power rating of distributed generation units; m and n are slopes of characteristics of P-δ and Q-$|\psi_V|$. The proposed method is shown in figure 2. The real and reactive power are split between the distributed generator units when the load is changed by bringing down δ, their own flux angle difference and $|\psi_V|$, amplitude of the flux.

III. SMALL SIGNAL ANALYSIS

A small signal analysis is proposed so as to investigate the system response which allows adjustment of the parameters which are to be controlled. The small-signal dynamics of droop controller of P-δ is obtained when linearizing (12) and (16) which yields

$$\Delta\delta(s)=\Delta\delta_n(s)-m(\Delta P_n(s)-\Delta P(s)) \quad (18)$$

$$\Delta P(s)=G_p.\Delta\delta(s) \quad (19)$$

where $G_p = \frac{\omega}{L}|\psi_E||\psi_V|\cos\delta$.

The low-pass filters are modeled as a first-order approximation which helps in calculation of instantaneous real power where the droop controller of P-δ equivalent circuit results from the signal model as shown in figure 3(a) where Δ indicates the countable values and ω_C denotes the low-pass filters angular cut-off frequency.

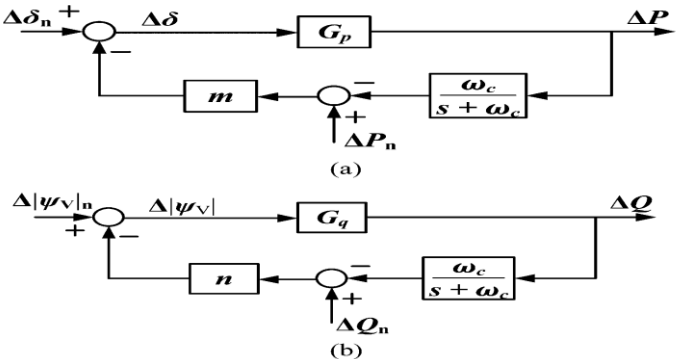

Fig. 3. Small-Signal model (a) Droop controller of P-δ. (b) Droop controller of Q-$|\psi_V|$.

Using ΔP as output and $\Delta\delta_n$ and ΔP_n as inputs and by superposition principle, the closed loop transfer function is derived.

$$\Delta P(s) = \frac{G_p(s+\omega_C)}{s+\omega_C-\omega_C mG_p}\Delta\delta_n(s) - \frac{mG_p(s+\omega_C)}{s+\omega_C-\omega_C mG_p}\Delta P_n(s) \qquad (20)$$

The characteristic equation derived from (20) where

$$s+\omega_C-\omega_C mG_p = 0 \qquad (21)$$

The eigen value of (21) is expressed as

$$\lambda_p = \omega_C(mG_p - 1) \qquad (22)$$

The small-signal dynamics of droop controller of Q-$|\psi_V|$ is obtained when linearizing (13) and (17) which yields

$$\Delta|\psi_V|(s) = \Delta|\psi_V|_n(s) - n(\Delta Q_n(s) - \Delta Q(s)) \qquad (23)$$

$$\Delta Q(s) = G_q.\Delta|\psi_V|(s) \qquad (24)$$

where $G_q = \frac{\omega}{L}|\psi_E|\cos\delta$.

The block diagram of Q-$|\psi_V|$ droop controller small-signal is shown in figure 3(b). Using ΔQ as output and $\Delta|\psi_V|_n$ and ΔP_n as inputs and by superposition principle, the closed loop transfer function is derived.

$$\Delta Q(s) = \frac{G_q(s+\omega_C)}{s+\omega_C-\omega_C nG_q}\Delta|\psi_V|_n(s) - \frac{nG_q(s+\omega_C)}{s+\omega_C-\omega_C nG_q}\Delta Q_n(s) \qquad (25)$$

The characteristic equation is derived as

$$s+\omega_C-\omega_C nG_q = 0 \qquad (26)$$

So, the eigen value of (26) yields

$$\lambda_q = \omega_C(nG_q - 1) \qquad (27)$$

The system eigen value placements vary with the droop slopes m and n from (22) and (27) which show the stability limits for the adjustment of the transient response of the system.

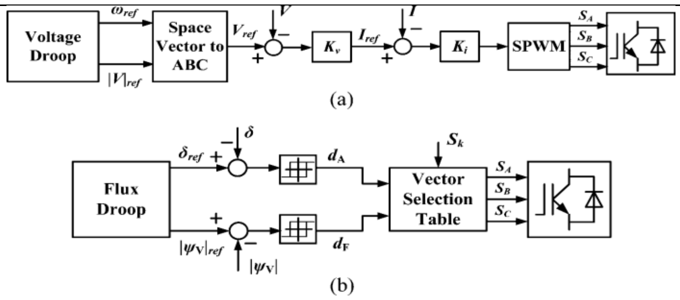

Fig. 4. Inverter control strategies schematic diagram (a) Actual voltage droop method multiloop feedback control. (b) Proposed virtual flux droop method DFC.

IV. INVERTERS DIRECT FLUX CONTROL

To achieve exact power sharing between the distributed generation units, the inverter produces this flux to control after obtaining the flux reference from the droop controller. In the actual voltage droop method, a multiloop feedback is utilized for controlling the inverters frequency and amplitude of the output voltage which are regulated for power sharing as shown in figure 4(a). As the droop controller output is flux reference so, in the proposed virtual flux droop method rather than the voltage reference, a DFC strategy is being used to generate this required flux, as assumed in figure 4(b).

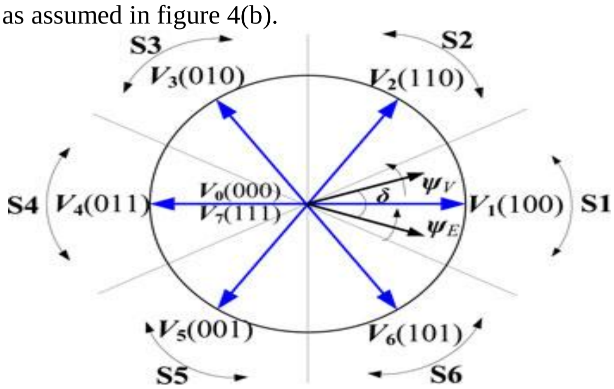

Fig. 5. Voltage vectors generated at inverter and division of the sectors.

For easy illustration of DFC, figure 5 shows voltage vectors of three-phase two-level inverter and ψ_V and ψ_E relationship. $|\psi_V|$ and δ are controlled by inverter using DFC which has a relative position to vector ψ_E. DFC strategy is based on the effects of each inverter voltage vector on $|\psi_V|$, δ are different which are listed in Table I [4].

TABLE I: VECTOR SELECTION STRATEGY

Sector number (Location of □V)	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
d_F = 1 (Increase $|\psi_V|$)	V_2	V_3	V_4	V_5	V_6	V_1
d_F = 0 (Decrease $|\psi_V|$)	V_3	V_4	V_5	V_6	V_1	V_2
Zero vector is applied to when $d_A = 0$						

DFC is implemented by using the signals d_F and d_A where these signals are obtained from hysteresis comparators using errors between reference and estimated values of $|\psi_V|$ and δ. The voltage vector is selected from Table I as per d_F, d_A and position of the inverter flux, φ_{fV}.

V. SIMULATION RESULTS

The study of microgrid structure is same as in [4]. The strategy of the proposed flux droop control and its performance are simulated using MATLAB/Simulink. The system parameters are listed in table II. The sampling frequency of the system is 20kHz and average switching frequency of each inverter is nearly 3.2kHz.

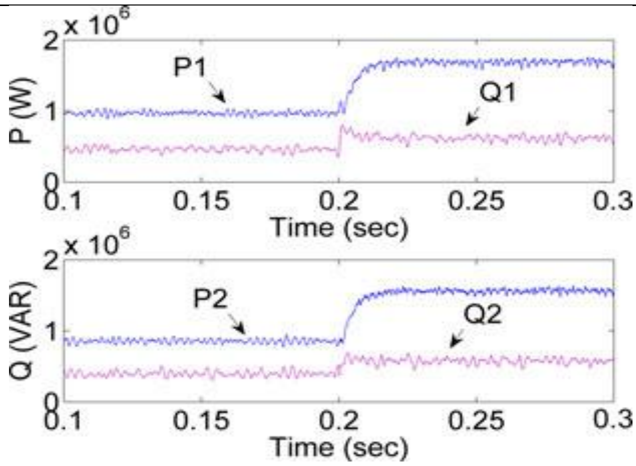

Fig. 6. Dynamic response of real and reactive power supplied by DGs for load changes.

TABLE II: SYSTEM PARAMETERS

Item	Symbol	Value
Line inductance	L_1 , L_2	8 mH
Line Resistance	R_1 , R_2	0.05 Ω
Filter Capacitance	C_1 , C_2	150 µf
Tie-line Inductance	L_t	6 mH
Tie-line Resistance	R_t	0.4 Ω
Nominal Voltage	E_n	3.6 kV_{rms}
Nominal Frequency	f_n	60 Hz
DGs output voltage	V_{dc1} , V_{dc2}	10 kV
Cut-off frequency	ω_C	10 rad/s

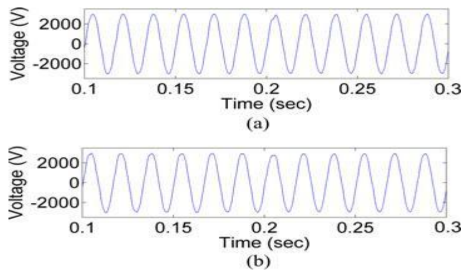

Fig. 7. Load-side voltages performance (a) phase A voltage of C_1 (b) phase A voltage of C_2.

The power sharing between the two inverters is shown in figure 6 for a load step change at 0.2s which is found that two DGs can take up the load change very fast so that the system reaches steady-point in 10ms. DG1 delivers more real power as it has steep slope (Section II). The results show the approach towards the novel approach of flux droop method for sharing of power in microgrid applications. The load-side performance is shown in figure 7. The voltage is stable and sinusoidal in nature, before, during as well as after the load changes which is an added advantage for the customers of microgrid.

VI. CONCLUSION

In this paper, a new approach for controlling power sharing between parallel connected inverters has been proposed for microgrid applications which are different to the actual voltage droop method. In the proposed droop controller, by bringing down the amplitude of the flux and by limiting the phase angle the power sharing is achieved. A DFC algorithm is being introduced in addition which controls the inverters in order to produce required flux from the proposed droop controller. So, feedbacks consisting of multiloops and PWM modulators are not used in the control structure. The proposed control strategy is effective and simple which is validated by simulation which highlights the use in microgrid applications.

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BIOGRAPHY

Kartheek Vankadara received M.E from Sathyabama University in 2011 in power electronics and industrial drives. Research interests include electric drives, control of power converters, smart grid, microgrid and green energy systems.

K.Jagadeesh Kumar received M.Tech from JNTUK University during 2014 in electrical power systems (high voltage engineering). Research interests include high voltage engineering and green energy systems.