Control Strategy of Single-Phase Voltage Controlled VSI Fed Load Connected to DC Microgrid

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Abstract—This paper presents a control strategy of single-phase Voltage Controlled Voltage Source Inverter (VCVSI) for interconnecting single-phase ac loads to the autonomous coordinated controlled DC Microgrid (DCMG) under constant as well as variable power generation with various varying loading conditions in an islanded mode. The autonomous DCMG consists of wind turbine, solar-photovoltaic, battery energy storage system, and various varying dc and ac (three-phase and single-phase) loads. The proposed control strategy maintains the sinusoidal load-voltage waveform at its rated voltage level with low Total Harmonic Distortion (THD) in voltage, and required power flow from DCMG to the single-phase ac load. The proposed control strategy has been implemented in d-q rotating reference frame. The measured output single-phase voltage and current of VCVSI are transformed into two-phase (α-β) stationary reference frame by using orthogonal vector generation method. The α-β components are transformed and controlled in d-q reference frame. The proposed control strategy uses the combination of “feed-forward” and “feedback” control signals to generate reference current signals for inner current controller. The design, modeling and simulation of proposed control scheme have been implemented in MATLAB/Simulink environment.

Keywords—DC microgrid, battery energy storage, single-phase voltage controlled voltage source inverter, solar photovoltaic, wind turbine, pulse width modulation.

I. INTRODUCTION

In recent years, Renewable Energy Sources (RES) have gotten a fast development and booming interest because of continuous energy demand growth, fast depletion of fossil fuels, serious environmental protection issues (such as: global warming and ozone layer reduction). The RES such as Wind Turbine (WT), Solar-Photovoltaic (SPV), Fuel Cell (FC), Micro-turbine (MT) generation etc. constitute the Distributed Generation (DG) with small-capacity generation ranging from 1kW to 10MW [1]. The direct connection of RES to the utility grid causes the problems of voltage rise, frequency variation, and protection problem, etc. [2], [3]. Therefore, the concept of “microgrid” is one of the solutions to integrate a mix of RES. The microgrids are classified as ac microgrid, and dc microgrid. The DC Microgrid (DCMG) is preferred over ac microgrid because of several advantages: 1) higher quality of power supply, 2) better reliability and uninterruptible supply, 3) higher efficiency, 4) each DG connected to DCMG can be easily operated coordinately because only dc voltage is to be controlled, and 5) due to absence of reactive power, it leads to better utilization and reduced total losses [2]-[5]. Due to these reasons, the dc microgrids are getting more popularity and increasing interest in the research.

Nowadays, Power-Electronic (PE) interface is used to integrate any type of DG, energy storage system, and various ac and dc loads to the DCMG. The Pulse Width Modulation (PWM) based Voltage Source Converters (VSCs) with insulated gate bipolar transistor switches are being used to provide voltage control, power flow control, system balancing, fault protection, and power sources with Maximum Power Point Tracking (MPPT) [6].

The proposed autonomous coordinated controlled “dc microgrid” consists of wind turbine, solar-photovoltaic, Battery Energy Storage System (BESS), and various varying dc and ac (three-phase and single-phase) loads. The DCMG is able to provide a high reliable and high quality power supply to the various varying dc and ac loads in an islanded mode. The single-phase ac load is connected to the DCMG through a single-phase Voltage Controlled Voltage Source Inverter (VCVSI). The dc voltage of DCMG is ±750V in the present study.

The single-phase Voltage Controlled Voltage Source Inverters (VCVSIs) have been widely used in RES, power supplies, power-quality controllers, and marine and military applications. In the DCMG, it is important to maintain a sinusoidal load-voltage for all ac loads in islanding mode. In conventional VCVSIs, the sinusoidal PWM generation is based on a reference sinusoidal waveform with the amplitude controlled by comparing an rms reference with the load-voltage rms value [7], [8]. This output-voltage feedback control is unable to maintain a sinusoidal load-voltage waveform for non-linear loads or when the dc voltage of DCMG fluctuates due to changing of power generation as well as loads.

To overcome these problems, this paper proposes a control strategy of single-phase VCVSI for connecting single-phase ac loads to the DCMG in an islanded mode. The task of the proposed control strategy is to maintain a sinusoidal load-voltage waveform at its rated voltage level with low Total Harmonic Distortion (THD) in voltage, and required power flow from DCMG to the load. The proposed control strategy maintains good output voltage regulation, high reliable and high quality power supply, and stabilizes dc voltage under constant as well as variable power generation and all various varying loads in an islanded mode. The proposed control strategy has been implemented for a 200kVA, 240V(rms), 50Hz single-phase full bridge VCVSI in d-q rotating Synchronous Reference Frame (SRF).
II. SYSTEM CONFIGURATION AND MODELING

A. DC Microgrid Configuration

The proposed architecture of “dc microgrid” for integration of RES is shown in Fig. 1. The DCMG facilitates the connections of any type of DG, BESS, and ac and dc loads. The autonomous control of DCMG has been achieved by using only the dc voltage of DCMG as common information. The main problem of the circulating current among the DG units connected to the DCMG, due to a voltage difference exists among them, has been eliminated with autonomous coordinated control strategy. Each DG unit should be controlled autonomously without communicating each other.

A control strategy for establishing constant dc voltage and maintaining power balance of autonomous coordinated controlled DCMG has been proposed and developed in [4]. In this paper, the same control strategy has been also used for establishing constant dc voltage and maintaining power balance of DCMG under variable power generation and various variable loads in islanded mode as in [4].

In the DCMG, a 600 kW autonomous control variable speed WT comprises of Double Fed Induction Generator (DFIG) with back-to-back (ac-dc-ac) PWM VSC: Rotor Side Converter (RSC), and Stator Side Converter (SSC). The RSC is used for MPPT, stator flux control, and to provide reactive power to DFIG through rotor circuit. The SSC is used to maintain active power balance in the system and constant dc link voltage of back-to-back converter. The WT generates a maximum active power of 600 kW at rated generating voltage of 690V (line-to-line, rms) for rated wind speed (12m/s), and a part of this power is consumed by a three-phase load connected to local area of the WT Generator (WTG). The remaining WT generated power is converted into dc power by maintaining the constant dc voltage (750V) through the bidirectional VSC and is transmitted through dc cable to the DCMG. When WT generation is zero at the wind speed below cut-in speed (4m/s) and above cut-off speed (25m/s) or WT power generation is less than the load demand in local area of WTG, then bidirectional VSC operates as an inverter to full fill the load demand in local area of WTG. The controller of this bidirectional VSC has been utilized also for establishing the constant dc voltage of DCMG.

A 100kW SPV generation comprises of a MPPT controller to track the maximum output power of SPV system based on the P-V characteristic as shown in Fig. 2, and the incremental conductance [9],[10]. In the positive-slope region \((dP/dV_p)>0\), the operation voltage is increased. On the other hand, in the negative-slope region \((dP/dV_p)<0\), the operation voltage is decreased. The peak power point starting from any operating point will be finally reached through a few steps of voltage adjustment. The SPV generates the dc power at lower voltage than the DCMG voltage and therefore a dc-dc boost converter is required to boost up the voltage up to DCMG voltage level, and also used for establishing the constant dc voltage in case of failure of the bidirectional VSC controller.

A BESS control unit is connected to the DCMG through a bidirectional dc-dc converter for controlling the charging and discharging of battery to compensate the power change caused by sudden changes in the power generation and loads. A surplus power is charged to the BESS. When the amount of the power generation is insufficient, the BEES discharges the power into the DCMG.

The rated loads connected to the DCMG are: (1) 200kW single-phase load (operating at 240V rms) through a full bridge VCVSI of 50 Hz frequency, (2) 100kW dc load operating at 220V dc through a dc-dc buck converter, and (3) 100kW three-phase load connected in local area of WTG. The rated total load connected to the DCMG is 400kW.

B. Modeling of DC Microgrid

1) Modeling of Wind Turbine Generation: The mechanical power extracted from the wind is given as [4], [11]:

\[
P_{mech} = \frac{\partial (KE_{wind})}{\partial t} = \frac{1}{2} C_P(\lambda, \theta) \rho_{air} A_b v_{wind}^3
\]

where and 

\[
C_P(\lambda, \theta) = 0.5176 \left( \frac{116}{\lambda} - 0.4\theta - 5 \right) e^{-21/\lambda} + 0.0068\lambda
\]

and 

\[
\lambda = \frac{\omega R_b}{v_{wind}}
\]

and 

\[
\lambda = \frac{1}{\lambda} + 0.08\theta - 0.035 \frac{1}{\theta^2 + 1}
\]

2) Modeling of Solar Photovoltaic System: The PV system is modeled as a current source to the DCMG. The current source is controlled by the MPPT algorithm to track the maximum power point of the PV array.

3) Modeling of Battery Energy Storage System: The BESS is modeled as a voltage source to the DCMG. The voltage source is controlled by the BESS controller to regulate the dc voltage of the DCMG.

Figure 1. Proposed architecture of dc microgrid for integration of renewable energy sources.
2) Modelling of Solar-Photovoltaic System: The equivalent circuit of a SPV array is shown in Fig. 3. The SPV array output current is given as [4],[10],[14]:

\[ I_{pv} = n_p I_{ph} - n_p I_{sat} \exp \left[ \frac{n_v}{n_s} + I(n_v R_{sc}/n_p) \right] - \left( \frac{n_v V_{oc}/n_s + I R_{sh}}{R_{sh}} \right) \]

where \( I_{pv} \) is the SPV array output current (A), \( V_{pv} \) is the SPV array output voltage (V), \( n \) is the number of SPV cells connected in series, \( n_v \) is the number of modules connected in parallel, \( q \) is the charge of an electron, \( k \) is Boltzmann’s constant, \( A \) is the p-n junction ideality factor, \( T_{ref} \) is the cell operating temperature (K), \( I_{sat} \) is the cell’s saturation current, \( R_{sh} \) is series resistance, and \( R_{dc} \) is the shunt resistance.

The photo-current depends on the Solar Irradiation (SI) and cell operating temperature, and can be expressed as:

\[ I_{ph} = I_{sc} + \sigma_{sc} \left( T_{cell} - T_{ref} \right) \left( \frac{S}{1000} \right) \]

(4)

The SPV cell’s saturation current varies with the cell operating temperature, and is expressed as:

\[ I_{sat} = I_{sc} \left( T_{cell}/T_{ref} \right) \exp \left[ f_{sc} \left( 1/T_{ref} - 1/T_{cell} \right) / k \right] \]

(5)

The reverse saturation current at reference temperature is given as:

\[ I_{rs} = I_{sc} \left( \exp \left( f_{sc} V_{oc}/N_s k T_{cell} \right) - 1 \right) \]

(6)

where \( I_{sc} \) is the SPV cell’s short-circuit current at standard test condition (STC) i.e. 25°C and 1kW/m², \( \sigma_{sc} \) is the cell’s temperature coefficient of short-circuit current, \( T_{ref} \) is the reference temperature, and \( S \) is the solar irradiation (kW/m²). \( E_g \) is the band-gap energy of the semiconductor used in the SPV cell (eV).

3) Modelling of Battery Energy Storage System: The dynamic model of lead acid battery, considering an equivalent capacitor (C_{eq}) as a controlled voltage source with an assumption of neglecting the difference between the charge and discharge resistances is shown in Fig. 4, [4], [15], [16].

The expressions of battery voltage for charge and discharge are given by (7) and (8), respectively as [4]:

\[ V_{batt} = V_0 - R_l i - k \frac{Q}{it - 0.1Q} - k \frac{Q}{Q-it} \cdot i^* + \exp(t) \]

(7)

\[ V_{batt} = V_0 - R_l i - k \frac{Q}{Q-it} - k \frac{Q}{Q-it} \cdot i^* + \exp(t) \]

(8)

where \( V_{batt} \) is battery voltage (V), \( V_0 \) is battery constant voltage (V), \( k \) is polarization constant (V/Ah), \( Q \) is battery capacity and \( it \) is battery charge (Ah), \( i \) is battery current (A), \( i^* \) is filtered current (A), \( R_l \) is battery resistance, \( \exp(t) \) is exponential zone voltage (V), \( R_p \) is self-discharge resistance, \( R_2 \) is over voltage resistance.

4) Modelling of Single-Phase Voltage Controlled Voltage Source Inverter: A single-phase full bridge VCVSI is shown in Fig. 5. The voltage and current equations of a single-phase full bridge VCVSI are given by (9) and (10), respectively [17].

\[ V_{conv} = R f_i i_L + L \frac{di_L}{dt} + V_a \]

(9)

\[ 0 = i_L - \frac{V_a}{Z} - C \frac{dV_a}{dt} \]

(10)

where \( V_{conv} \) is inverter output voltage, \( L \) is inductor of filter, \( C \) is capacitor of filter, \( R \) is resistance of inductor filter, \( i_L \) is current through the inductor, \( V_a \) is voltage across the capacitor or load, \( Z \) is the impedance of the load, and \( k = -1, 0, \) or -1) is the control variable depending on the state of switches in the full bridge.

The voltage and current equations of a single-phase full bridge VCVSI in d-q rotating reference frame are given by (11) and (12), respectively [17], [18].

\[ V_{conv,d} = R f_i i_d + L \frac{di_d}{dt} - \omega L f_i i_q + V_q \]

(11)

\[ V_{conv,q} = R f_i i_q + L \frac{di_q}{dt} - \omega C f_i i_d + V_q \]

(12)

where \( \omega \) is the angular supply frequency.

III. PROPOSED CONTROL STRATEGY OF SINGLE PHASE VOLTAGE CONTROLLED VOLTAGE SOURCE INVERTER

The proposed control strategy of single-phase full bridge VCVSI is shown in Fig. 6. In this control strategy, the measured single-phase output voltage and current of VCVSI are transformed into two-phase (α-β) stationary SRF by using orthogonal vector generation. In orthogonal vector generation, the measured single-phase voltage/current is assumed to be equal to the α-axis component of voltage/current in the α-β stationary SRF, and β-axis component of voltage/current has been obtained by introducing a phase delay of π/2 rad on the voltage/current as shown in Fig. 7. This phase delay is obtained by using a transport delay time of T/4 (where T=1/f=1/50 sec, fundamental period) i.e. 5ms. The single-phase Phase-Locked Loop (PLL) based on d-q rotating SRF is used to obtain the phase angle information of the voltage, and to track the supply.
frequency. The input signals given to the PLL are α-axis voltage ($V_{α}$) and β-axis voltage ($V_{β}$). The voltage/current components of α-β stationary SRF have been transformed into d-q rotating reference frame by using Parks transformation. The dc voltage controller (shown in Fig. 8.) provides the d-axis reference current as “Feed-Forward” (FF) control loop signal.

An ac voltage controller with cross coupling of filter capacitor is shown in Fig. 9. The transformed voltages of d-q rotating SRF are compared with the d-q reference voltages ($V_{d,ref}=1.0$ p.u. and $V_{q,ref}=0$). These voltage errors are sent to the PI controllers. This ac voltage controller generates the reference currents of d-q rotating SRF as “Feed-Back” (FB) control signals in this control strategy.

The inner current controller with cross coupling of filter inductors is shown in Fig. 10. The transformed currents of d-q rotating SRF are compared with the d-q reference currents, and these current errors are sent to the PI controllers. The d-q reference currents used in the inner current controller are obtained by the combination of FF and FB control loop signals as shown in Fig. 6. The FF control signal allows to stabilize dc voltage and to improve the stability of the system. The FB control signal maintains good output voltage regulation, and provides high reliable and high quality power supply. The inner current loop is faster than outer voltage loop. The inner current loop allows faster transient response and improved THD under nonlinear loads or dc voltage fluctuations due to changing of power generation as well as loads.

The current equations for ac voltage controller and voltages equations for inner current controller are expressed by (13) and (14) respectively.

$$\begin{align*}
I_{d\_ref} &= \left(V_{d\_ref} - V_d\right) \left(\frac{K_{PvC} + K_{Iv}}{s}\right) - \omega C_f V_q \\
I_{q\_ref} &= \left(V_{q\_ref} - V_q\right) \left(\frac{K_{PvC} + K_{Iv}}{s}\right) + \omega C_f V_d \\
V_{d\_ref} &= V_d + I_{d\_ref} - I_d \left(\frac{K_{Pc} + K_{Ic}}{s}\right) - \omega L_f I_q \\
V_{q\_ref} &= V_q + I_{q\_ref} - I_q \left(\frac{K_{Pc} + K_{Ic}}{s}\right) + \omega L_f I_d
\end{align*}$$

The PI-based approaches are efficiently used for current regulation of VSI and good harmonic performance. The parameters of PI controllers for stable closed loop system are determined by using bode plot technique. The optimized parameters of PI controllers for dc voltage controller, outer ac voltage controller, and inner current controller are $K_{Pdc}=0.004$, $K_{Idc}=1.25s^{-1}$; $K_{Pac}=6.5$, $K_{Iac}=500s^{-1}$; and $K_{Pc}=4$, $K_{Ic}=200 s^{-1}$, respectively. The calculated parameters of LC filter for a $200kVA, 240V$(rms), $50Hz$ VCVSI are $L_p=1.068mH$, $R_p=3.3553mΩ$, and $C_f=30µF$.

IV. SIMULATION RESULTS

Three case studies have been demonstrated to show the ability of proposed control strategy of single-phase VCVSI and autonomous coordinated controlled DCMG in an islanded mode in MATLAB/Simulink environment.

A. Case1. Constant Power Generation and Constant Total Load While Variable Single-Phase AC Load

In this mode, the power generations by WT (at wind speed $8m/s$), by SPV DGs (at STC), and total power generation (400kW constant) are as shown in Fig. 11, for 11:00AM to 1:30PM in a day. The total load demand connected to the DCMG has been assumed to be constant of 400 kW (rated), while single-phase ac load and other two loads connected to the DCMG are variable as shown in Fig. 12. During this mode, the proposed control strategy of single-phase VCVSI maintains a sinusoidal load-voltage waveform at rated voltage (240V rms) with low THD (1.72%) in voltage, and required power flow from DCMG to the load as, shown in Fig. 13. The dc voltage of the DCMG is also maintained constant (750V) during the operation as shown in Fig. 14.
B. Case2. Constant Power Generation and Variable Total Load While Constant Single-Phase AC Load

In this mode, the total power generation is constant and same (400kW) as in case1. The total load demand connected to the DCMG is variable as shown in Fig. 15. While single-phase ac load connected to VCVSI is constant, other loads connected to DCMG are variable as shown in Fig. 16. During this mode, the proposed control strategy of single-phase VCVSI maintains a sinusoidal load-voltage waveform at rated voltage with low THD (1.6% - 2.5%) in voltage as shown in Fig. 17, and required power flow from DCMG to the load. The power gap between the generation and total load demand is full filled by BESS as shown in Fig. 15. The dc voltage of DCMG is also maintained constant (750V) as shown in Fig. 18.

C. Case3. Variable Power Generation and Variable Total Load With Variable Single-Phase AC Load

In this mode, the power generation by WT depends upon wind speed as shown in Fig. 19. The power generation by SPV depends upon SI and temperature during the day from 6AM to 6PM, as shown in Fig. 20. The SPV power generation increases with increasing SI or vice-verse, and SPV power generation decreases with increasing temperature or vice-verse. The total power generation is variable and total load demand connected to the DCMG is also variable as shown in Fig. 21. The power gap between the generation and total load demand is balanced by BESS as shown in Fig. 21. The total load connected to the DCMG varies according to the residential load curve [19] for a day (24 hours), as shown in Table I with base quantities (base power = 400kW and base voltage = 750V). The load is assumed to be constant for next two hours. Here, all individual loads connected to the DCMG vary according to this load curve, as shown in Fig. 22. The dc voltage of DCMG has been also maintained constant during the operation as shown in Fig. 23. During this mode the proposed control strategy of single-phase VCVSI maintains a sinusoidal load-voltage waveform at rated voltage (240V rms) with low THD (1.6% - 4%) in voltage, and required power flow from DCMG to the load properly as shown in Fig. 24.

<table>
<thead>
<tr>
<th>Time (Hrs.)</th>
<th>7PM</th>
<th>9PM</th>
<th>11PM</th>
<th>1AM</th>
<th>3AM</th>
<th>5AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (p.u.)</td>
<td>1.0</td>
<td>0.85</td>
<td>0.7</td>
<td>0.55</td>
<td>0.47</td>
<td>0.4</td>
</tr>
<tr>
<td>Time (Hrs.)</td>
<td>7AM</td>
<td>9AM</td>
<td>11AM</td>
<td>1PM</td>
<td>3PM</td>
<td>5PM</td>
</tr>
<tr>
<td>Load (p.u.)</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.85</td>
<td>1.05</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Uncertainty and intermittent characteristics of wind speed, SI, and temperature are considered in the system operation. It is assumed that wind speed is constant for next four hours, and SI and temperature is constant for next one hour.

Figure 2. Single-phase load voltage (case3) [zoomed at transient, t=7:00PM].

V. CONCLUSIONS

In this paper a control strategy of single-phase VCVSI for integrating single-phase ac load to the DCMG has been proposed and implemented in d-q rotating SRF. An orthogonal vector generation is used to transform single-phase voltage/current into two-phase (α-β) stationary SRF voltage/current. The purpose of this control strategy is to maintain a sinusoidal load-voltage waveform of 50 Hz frequency at the rated voltage (240V rms) with low THD (1.6% - 4%) in voltage, and required power flow from DCMG to the load efficiently for constant as well as variable power generation and all variable varying loads in an islanded mode. The proposed control strategy provides good output voltage regulation performance, and high reliable and high quality power supply to the single-phase ac load. This also allows faster transient response under dc voltage fluctuations due to changing of power generation as well as loads. Thus, the single-phase VCVSI with proposed control strategy operates satisfactorily under constant as well as variable power generation and all variable loads for both the transient and steady state conditions. The proposed DCMG provides reliable, stable and high quality power supply at desired constant dc voltage under various varying loads in an islanded mode, and also facilitates the connections of any type of DGs, BESS, and various ac and dc loads.

VI. REFERENCES


