An Advanced CHB Multilevel Inverter Using Fuzzy Logic Controller in Non Linear and Unbalanced Conditions

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Abstract: This paper presents a control strategy for an islanded medium voltage microgrid to coordinate hybrid power source (HPS) units and to control interfaced multilevel inverters under unbalanced and nonlinear load conditions. The proposed HPS systems are connected to the loads through a cascaded H-bridge (CHB) multilevel inverter. The CHB multilevel inverters increase the output voltage level and enhance power quality. The HPS employs fuel cell (FC) and photovoltaic sources as the main and super capacitors as the complementary power sources. Fast transient response, high performance, high power density, and low FC fuel consumption are the main advantages of the proposed HPS system. The proposed control strategy consists of a power management unit for the HPS system and a voltage controller for the CHB multilevel inverter. Each distributed generation unit employs a multi proportional resonant controller to regulate the buses voltages even when the loads are unbalanced and/or nonlinear. Digital time-domain simulation studies are carried out in the PSCAD/EMTDC environment to verify the performance of the overall proposed control system.

Index Terms—Cascaded H-bridge (CHB) multilevel inverter, fuel cell (FC), hybrid power source (HPS), multi proportional resonant (multi-PR), photovoltaic (PV), super capacitor (SC).

I. INTRDUCTION

Today, new advances in power generation technologies and new environmental regulations encourage a significant increase of distributed generation resources around the world. Distributed generation systems (DGS) have mainly been used as a standby power source for critical businesses. For example, most hospitals and office buildings had stand-by diesel generators as an emergency power source for use only during outages. However, the diesel generators were not inherently cost-effective, and produce noise and exhaust that would be objectionable on anything except for an emergency basis.

On the other hand, environmental-friendly distributed generation systems such as fuel cells, micro turbines, biomass, wind turbines, hydro turbines or photovoltaic arrays can be a solution to meet both the increasing demand of electric power and environmental regulations due to green house gas emission. The centralized and regulated electric utilities have always been the major source of electric power production and supply. However, the increase in demand for electric power has led to the development of distributed generation (DG) which can complement the central power by providing additional capacity to the users.

These are small generating units which can be located at the consumer end or anywhere within the distribution system. DG can be beneficial to the consumers as well as the utility. Consumers are interested in DG due to the various benefits associated with it: cost saving during peak demand charges, higher power quality and increased energy efficiency. The utilities can also benefit as it generally eliminates the cost needed for laying new transmission/distribution lines. Distributed generation employs alternate resources such as micro-turbines, solar photovoltaic systems, fuel cells and wind energy systems. This thesis lays emphasis on the fuel cell technology and its integration with the utility grid.

Converter-based DG units may introduce harmonics into a micro grid and result in power quality issues. However, well- designed and well-controlled converters are able to improve the power quality and efficiency of the micro grids. Besides the primary purpose of the DG units for power generation, many services can also be provided, e.g., voltage support, power fac- tor correction, flicker mitigation, and harmonic and unbalance voltage compensation. In this paper, a voltage controller for a CHB multilevel inverter is proposed to enhance dynamic responses and power quality of micro grid in the presence of unbalanced and nonlinear loads. The multi proportional resonant (multi-PR) controller is used to regulate the load voltage. When the load is nonlinear, the use of a multi-PR controller is more advantageous as compared to the conventional PR controllers.

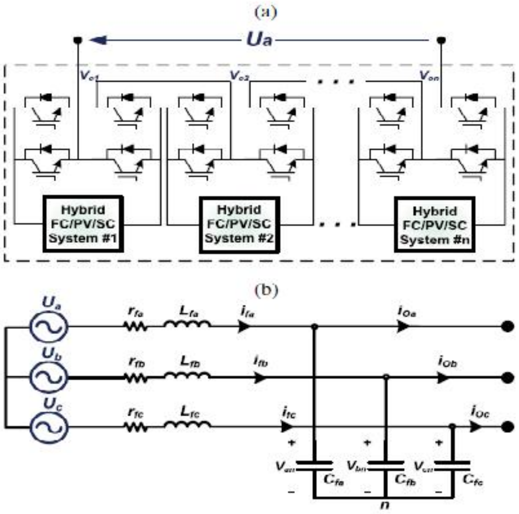


Fig.1. (a) One-phase structure of a CHB multilevel inverter and (b) circuit diagram of a three-phase, three-wire DG unit.

II. PROPOSED DG MODEL

Fig. 2 shows the schematic diagram of the proposed system. Conventional signs of voltages and currents components are also indicated in this schema, where Rc and Lc represent the equivalent resistance and inductance of the ac filter, coupling transformer, and connection cables; Rs and Ls represent the grid resistance and inductance up to the point of common coupling (PCC), respectively; vk(k=1,2,3) is the supply voltage components at the PCC; vs kis the grid voltage components; vdc is the dc-link voltage; and isk, ilk, and ick are grid, load, and DG current components, respectively. In addition, the DG resources and additional components are represented as a dc current source which is connected to the dc side of the converter.

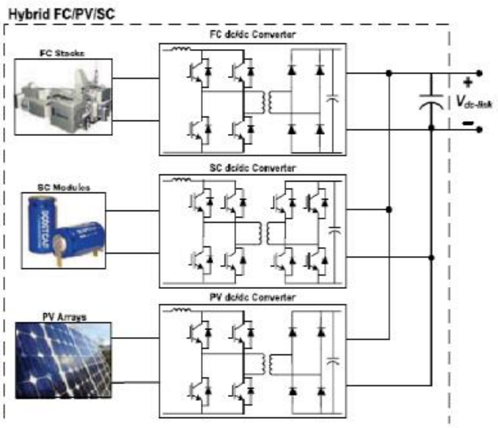


Fig. 2. Proposed structure of the hybrid FC/PV/SC power source.

In order to achieve high efficiency and galvanic isolation, the power sources of each HPS are connected to the dc link of multilevel inverter modules through full-bridge dc/dc converters. The unidirectional and bidirectional full-bridge converters of the FC and SC units make the output current smooth and regulate the output voltages of the units at the desired values. Moreover, the bi directional power flow of the SC module increases power management flexibility. The full-bridge converter of the PV unit is controlled such that the maximum power point tracking (MPPT) is achieved.

III. OPERATION PRINCIPLES OF THE PROPOSED CONTROL STRATEGY

The proposed control strategy comprises 1) a power management for the HPS system, and 2) a voltage control for the CHB multilevel inverter. To manage the power and regulate the dc-link voltage of the HPS unit, two independent controllers are designed. Furthermore, a voltage control loop is proposed to provide a set of balanced sinusoidal voltages at the terminals of CHB multilevel inverter in the presence of nonlinear and unbalanced loads.

A. Control Strategy of the HPS

The proposed control strategy of the hybrid FC/PV/SC power source is shown in Fig. 3. The HPS uses the FC and PV units as the main power sources and the SC as the complementary power source. The PV unit enables the FC to obtain an appropriate operating point at which the hydrogen consumption is minimized. The SC modules support the FC and PV to achieve good transient response and meet the grid power demand. The utilization of three separate full-bridge converters in parallel facilitates the power management capability and increases the overall performance and flexibility of the HPS.

According to the proposed control strategy, the dc current of the SC module must accurately follow its reference to zero. A PI controller determines the duty cycle of the FC converter. The reference signal generated by the controller is limited not to exceed the FC capability in injecting the current. The corresponding limitation for the current demand is calculated according to the typical range of utilization factor, which ensures the desired operation of FC stack. Furthermore, the FC current slope is limited to avoid the fuel starvation phenomena and to guarantee the safe operation of the FC stack. For control design purposes, the dc/dc converters are modeled using the state-space averaging technique.

$$\frac{\hat{i}_L}{\hat{d}} = \frac{\frac{2I_L}{(1-D)}\left(1+\frac{R_{FC}C_{FC}}{2}S\right)}{1+\frac{n^2L_{FC}}{R_{FC}(1-D)^2}S+\frac{n^2L_{FC}C_{FC}}{(1-D)^2}S^2}$$

where IL is the inductor current, D is the nominal duty cycle, n is the transformer winding ratio, and LFC, CFC, and RFC are, respectively, the inductor, capacitor, and equivalent output resistor of the FC converter.

TABLE I
PARAMETERS OF CONTROLLERS

Controller	Parameters Value
FC Converter	k_p=0.031 , k_I=0.01
SC Converter	k_p=6e^{-5} , k_I=0.012
Current controller	k_c=0.9
Lead compensator ($C(s)$)	k_1=1 , k_2=67 , k_3=11700
$G_1(s)$	k_4=5.8 , k_5=5170 , k_6=5.4e6
$G_5(s)$	k_7=7.9 , k_8=2860 , k_9=4.5e6
$G_7(s)$	k_{10}=8.3 , k_{11}=3420 , k_{12}=1e7

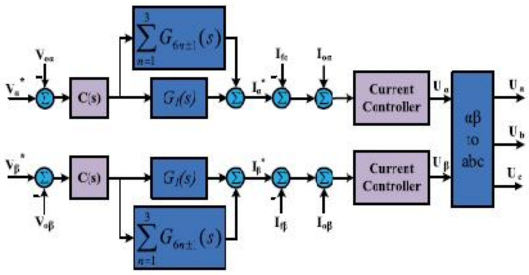


Fig. 3. Block diagram of the proposed multi-PR controller.

B. Control Strategy of the Inverter

The magnitude and frequency of the reference voltage (V ∗ α and V ∗ β) are determined by the droop controller. To protect the inverter against over current and to increase the internal stability of the voltage control loop, an inner current loop is also incorporated. The current controller is a simple gain, kc, whose value is calculated such that the damping factor of the dominant poles of the inner loop system becomes 0.7. To eliminate the impact of load dynamics, the out- put currents, i.e., Ioα and Ioβ, are feed forward to the output of the voltage control loop. The resultant signals are then applied to the current controllers to generate the control signals Uα and Uβ. Finally, the control signals in αβ-frame are transformed to the abc-frame and then applied to the modulation unit.

According to the internal model principle, a reference (disturbance) can be asymptotically tracked (rejected) if the controller contains the Laplace transform of the reference signal in its transfer function. The output currents (Ioα and Ioβ), which can be considered as disturbances in the control system, contain fundamental and higher order harmonics when the load is nonlinear. Notice that since the loads are not connected to the microgrid buses via Y/Δ transformers, a zero-sequence or third-order harmonic current exists in the inverter side of the DG units. To achieve zero steady-state error in the presence of harmonic currents, a multi-PR controller is proposed as follows:

$$K(s) = C(s)\Big[G_1(s) + G_5(s) + G_7(s)\Big]$$

where C, G_1, G_5, and G_7 are

$$C(s) = k_1\frac{s+k_2}{s+k_3}$$

$$G_1(s) = k_4\frac{s^2+k_5 s+k_6}{s^2+\omega_c s+\omega_0^2}$$

$$G_5(s) = k_7\frac{s^2+k_8 s+k_9}{s^2+5\omega_c s+(5\omega_0)^2}$$

$$G_7(s) = k_{10}\frac{s^2+k_{11} s+k_{12}}{s^2+7\omega_c s+(7\omega_0)^2}.$$

G5(s) and G7(s) are harmonic compensators, and C(s) is a lead compensator which is employed to guarantee the robust stability of the closed-loop voltage control system. According to the bandwidth of the voltage control system (400 Hz), only the fifth and seventh-order harmonics can be compensated. In (4), the co efficient ki,i=1,...,12, are the design parameters of the multi-PR controller. To obtain the coefficients k is, the following performance characteristics are to be met. 1) The closed-loop system achieves good stability margins. 2) The bandwidth of the open-loop system should be less than 10% of the switching frequency. 3) The reference should be tracked within two cycles with zero steady-state error. 4) The disturbance (harmonic currents) should be rejected. Considering the aforementioned performance indices and using MATLAB SISO tools, the coefficients of the controller are designed and listed in Table I.

IV. SIMULATION RESULTS

To investigate the effectiveness of the proposed control strategy, the microgrid system of Fig. 4 is simulated in the PSCAD/EMTDC environment. The micro gird system is com- posed of a three-feeder distribution system and two DG units. Each DG unit is connected to the corresponding feeder using a CHB multilevel inverter. For the sake of simplicity, each DG unit employs a two-cell CHB multilevel inverter. The loads are connected to the feeders via Y/Δ transformers. It is assumed that the microgrid system operates in the islanded mode. Each CHB multilevel inverter is equipped with the proposed multi- PR controller, HPS power management, and a droop control strategy.

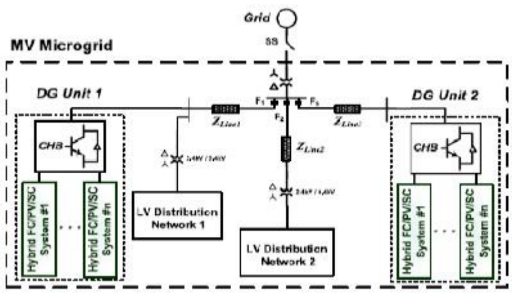
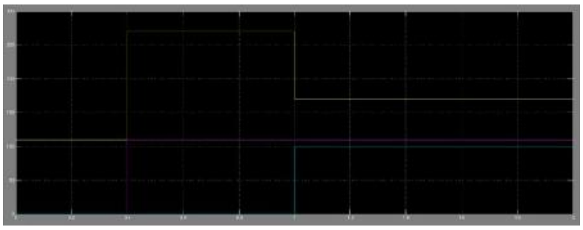


Fig. 4. Single-line diagram of MV microgrid consisting of two DG units.

The slope of FC current is limited to±0.0625 p.u.s−1 to pre vent the fuels starvation phenomenon. The PV system is equipped with an MPPT control strategy. Maxwell Technologies Boost- cap BMOD0165-type SC is used as the energy storage. The dc-link voltage of each HPS system is regulated at 1 kV. The microgrid parameters are given in Table II.

TABLE II
PARAMETERS OF THE MICROGRID'S SUBSYSTEMS

Parameter	Representation	Value
	HPS Parameters	
P_{FC}	Rated power	150 kW
P_{PV}	Rated power	50 kW
V_{MPPT}	MPPT voltage	250-300 kV
f_{sw}	Switching frequency	1 kHz
n	converters winding ratio	2
L_{FC}	FC Inductor	3.6 mH
L_{SC}	SC Inductor	4.1 mH
C_{FC}	FC converter capacitor	1.6 mF
C_{SC}	SC converter capacitor	1.5 mF
	Inverter Parameters	
P_{ac}	Rated power	1200 kVA
V_{ac}	Nominal ac voltage	2.4 kV
$C_{dc-link}$	dc-link capacitance	2000μF
r_f	Resistance	1.5 mΩ
L_f	Inductance	0.5 mH
C_f	Capacitance	100 μF
m_{DG_1}, m_{DG_2}	P-f droop coefficient	$8e^{-4}$, $16e^{-4}$ Hz/kW
n_{DG_1}, n_{DG_2}	Q-V droop coefficients	0.08, 0.16 V/kVAr
	Lines Parameters	
Z_{line1}	5.7 km overhead line	0.02 + j 0.045 Ω
Z_{line2}	4 km overhead line	0.015 + j 0.036 Ω
Z_{line3}		0.0 + j 0 Ω



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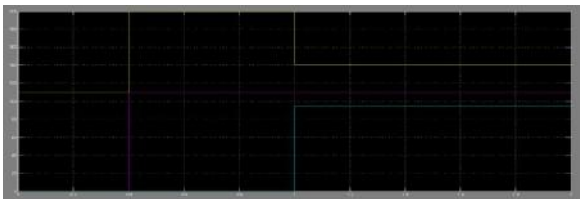

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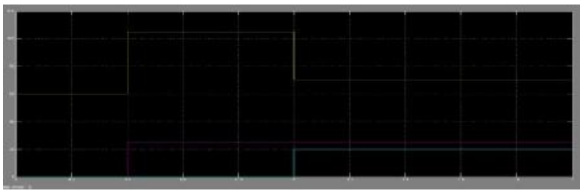
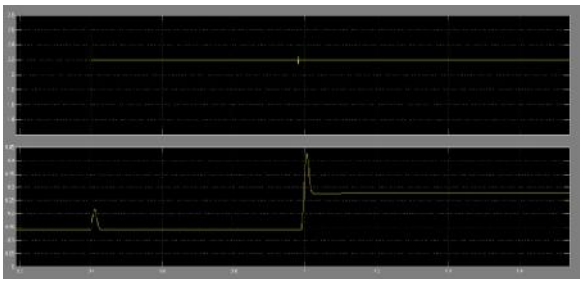


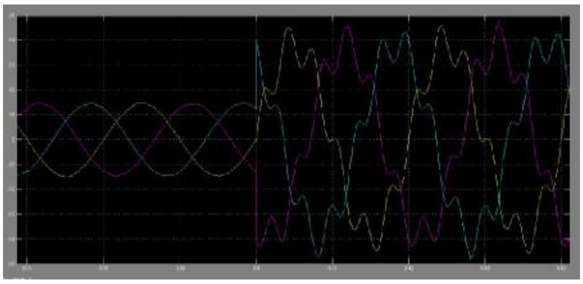
c.

Fig.5. Microgrid response to the unbalanced and nonlinear load changes applied to feeder F1; positive sequence, negative-sequence, and harmonic components of loads currents at (a) feeder F1 and (b) feeder F2.
(c) fedder F2



a.

Fig.6. Microgrid response to the unbalanced and nonlinear load changes applied to feeder F1;positive sequence, negative sequence, and harmonic currents of DG1



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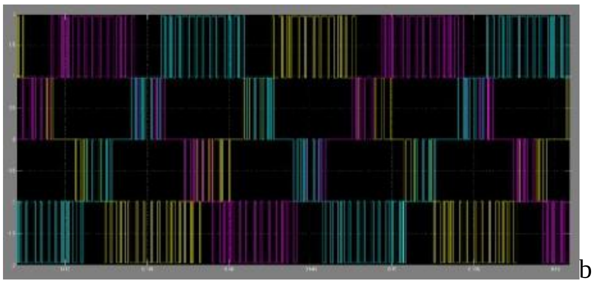

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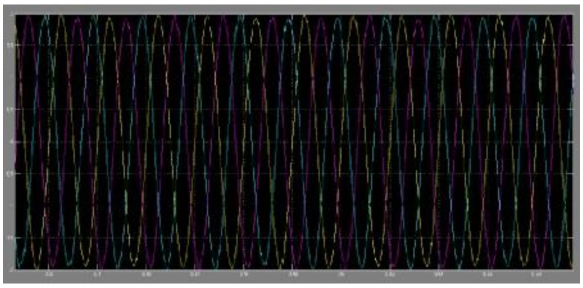

c.

Fig.7. (a) Instantaneous current waveforms, (b) five level-inverter output voltage, and (c) voltage waveforms of each phase of DG1's CHB inverter due to the nonlinear load connection to feeder F1.

At t = 15 s, the radiation intensity drops and the power of PV units decreases to 80% in about 2 s, as depicted in Fig.5. As shown in Figs. 6 and 7, the SC module compensates the power shortage of the FC stack, while the FC stack increases its output power at a limited response rate.

V.CONCLUSION

This paper presents an effective control strategy for an is- landed microgrid including the HPS and CHB multilevel inverter under unbalanced and nonlinear load conditions. The proposed strategy includes power

management of the hybrid FC/PV/SC power source and a voltage control strategy for the CHB multilevel inverter.
His area of interests includes An Advanced CHB Multilevel Inverter Using Fuzzy Logic Controller in Non Linear and Unbalanced Conditions.

The main features of the proposed HPS include high performance, high power density, and fast transient response. Further more, a multi PR controller is presented to regulate the voltage of the CHB multilevel inverter in the presence of unbalanced and nonlinear loads. The performance of the pro- posed control strategy is investigated using PSCAD/EMTDC software.

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