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## Analysis of Single-Stage 9-Level Current-Source Inverter to Interface Fuel Cell with Grid

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**Abstract:** Renewable energy sources can be used for electric power generation to supply specific devices in distributed systems such as smart grids. Hydrogen fuel cells have proven to be an effective solution to produce electrical energy with fairly good efficiency and minimum environmental pollution. A single-stage solution to interconnect a fuel cell with a low-voltage distribution system is proposed in this concept. The traditional boost dc/dc converter plus voltage source inverter is replaced by a single-stage multilevel current-source inverter (MCSI). The MCSI can both interconnect to the grid and perform the maximum power point tracking algorithm. This novel single-stage converter approach provides active power to the grid, power factor compensation, and reduction of the line current harmonic content. The proposed concept can be implemented to 9 level current source inverter for fuel cell the simulation results are presented by using Matlab/Simulink software.

**Keywords:** Fuel Cells, Grid Interface, Maximum Power Point Tracking (MPPT), Multilevel Current-Source Inverter (MCSI).

### I. INTRODUCTION

With increasing concern of global warming and the depletion of fossil fuel reserves, many are looking at sustainable energy solutions to preserve the earth for the future generations. Other than hydro power, photovoltaic energy holds the most potential to meet our energy demands. Alone, solar energy is capable of supplying large amounts of power but its presence is highly unpredictable as it can be here one moment and gone in another. Similarly, solar energy is present throughout the day but the solar irradiation levels vary due to sun intensity and unpredictable shadows cast by clouds, birds, trees, etc. Fuel Cell converts the chemical energy to electrical energy with higher efficiency [1-3]. The common inherent drawback of photovoltaic systems is their intermittent natures that make them unreliable. However, by combining these two intermittent sources and by incorporating maximum power point tracking (MPPT) algorithms, the system's power transfer efficiency and reliability can be improved significantly. The integration of renewable energy sources and energy-storage systems has

been one of the new trends in power-electronic technology. The increasing number of renewable energy sources and distributed generators requires new strategies for their operations in order to maintain or improve the power-supply stability and quality. Combining multiple renewable resources via a common dc bus of a power converter has been prevalent because of convenience in integrated monitoring and control and consistency in the structure of controllers as compared with a common ac type [4-6].

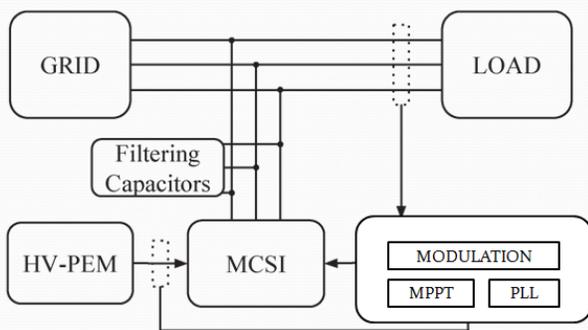
Dynamic performance of Fuel cell and solar system is analyzed. A system model was developed and compared with a real system. Several methodologies for optimal design or unit sizing. Most applications are for stand-alone operation, where the main control target is to balance local loads. A few grid-connected systems consider the grid as just a back-up means to use when there is insufficient supply from renewable sources. They are originally designed to meet local load demands with a loss of power-supply probability of a specific period. Such hybrid systems, focusing on providing sustainable power to their loads, do not care much about the quality or flexibility of power delivered to the grid. From the perspective of utility, however, a hybrid system with less fluctuating power injection or with the capability of flexibly regulating its power is more desirable. In addition, users will prefer a system that can provide multiple options for power transfer since it will be favorable in system operation and management. Control strategies of such a hybrid system should be quite different from those of conventional systems [7-10]. Classical techniques of maximum power tracking are applied in PV array control. Dynamic modeling and simulations were based on Power System Computer Aided Design with MATLAB/SIMULINK. The program was based on Dommel's algorithm, specifically developed for the simulation of high-voltage direct current systems and efficient for the transient simulation of power system under power-electronic control.

In this paper, a single-rating inductor MCSI is employed to feed a three-phase load. The converter consists of a number of identical modules, which determine the different

current levels. Each module uses two balance inductors and six power switches. All inductors of every module should carry the same amount of current. The current flowing through the inductors can be balanced, and switching frequency can be reduced by applying a state-machine modulation that properly uses redundant zero states [11-12]. Industrial assemblies are easy to develop and to operate because all modules are identical. The behavior of this converter is very different from the behavior of the traditional MVSI. Herein, each module carries a fraction of the load current, and there is no separation of modules or switches per phase as occur in an MVSI. In most MVSI, when a low voltage is delivered to the load, the outermost switches stop working, and the load current is only delivered by the switches connected close to the central point of the converter. This situation does not occur with the topology used for this MCSI. This converter with the proposed modulation always splits the output current among all the switches regardless of the modulation index ( $m_a$ ). The modulation and gate-drive control logic are implemented, which is a powerful cost-effective solution. It allows complex logical and control algorithms, fast speed, and multiple input/output pins, which becomes particularly attractive for multilevel-converter control [13]. The behavior of the MCSI and the modulation technique has been previously presented. In this paper, the SPWM logic has been modified for better performance implementation. A simple approach is presented showing that current balance can be provided by adapting a well-known SPWM strategy while minimizing switching speed using a novel sequential machine design [14].

**II. SYSTEM DESCRIPTION**

A three-phase MCSI is used to inject the current provided by a proton exchange membrane (PEM)-type fuel cell to a  $3 \times 190$  VLL, 50-Hz, and three-phase utility grid, as shown in the basic schematic in Fig. 1.



**Fig. 1. System layout.**

An MCSI has three main advantages. First, it can be connected directly to the utility grid without any coupling inductors. Second, it can drain constant current from the fuel cell. Third, it requires smaller input voltage compared with traditional voltage inverters. Current source inverters (CSIs) have a large inductor on the dc side; this means that the current drained from the energy source has a low ripple. At the output, a small capacitor bank is required to smooth

commutation currents, avoiding overvoltages due to inductances in the current path. The control algorithms and modulation signals of the MCSI are implemented, as well as data acquisition and processing. A simple controller based on a Park transform (dq0) controlling the MCSI output current is enough to compensate both power factor and harmonics caused by the load on the current of the grid. Moreover, the MPPT controller acts directly over the active power set point of the system. If required, a smart grid control can adjust the power provided to the grid to a suitable level.

**A. MCSI**

The schematic of the inverter is shown in Fig. 2. It consists of three identical modules with the capability of producing seven levels in the output current. Each module has six switches with bidirectional voltage blocking capabilities and two inductors to balance the current through them. All the balance inductors are identical and carry the same average current, simplifying the design, construction, operation, and maintenance of the inverter. The current of each module can be balanced by the use of the well-known phase-shifted carrier sinusoidal pulse width modulation (PSC-SPWM), in which gate signals are calculated comparing the reference signals with three equally phase-shifted triangular waveforms. A block diagram of the PSC-SPWM is shown in Fig. 3, and the SPWM of the first module is displayed in Fig. 4. Power converters can be classified into voltage-source inverters (VSIs) and CSIs depending on the topology of the power supply. The implementation of the SPWM in a CSI is not as straightforward as that in a VSI. The gating signals for a VSI are generated by the comparison of one triangular carrier with three sine waves. The driving signals for a CSI need more logic manipulation to generate the desired current level at the load while assuring current continuity in all the inductors. First, the standard SPWM signals PA, PB, and PC in Fig. 4(b) are generated by the comparison of one triangular with three sine waves. These phase signals are XORed two at a time to obtain a logic equivalent to the line-to-line voltage in a VSI.

The obtained signals are ANDed with the required sign of the current in each phase, or its logic complement, to obtain the firing signals of upper or lower switches, respectively [as shown in Fig. 4(c)]. These signals cannot directly drive the gates of the insulated-gate bipolar transistors (IGBTs) since they generate zero states by turning off all switches [Time “z” in Fig. 4(c)], thus not allowing inductor’s current continuity. The zero states generated by the SPWM logic should be recognized and replaced by adequate zero states, taking advantage of the redundancy of the CSI topology. A detailed analysis of the circuit topology and the modulation method can be found. Each module can produce zero-current state in three different ways by turning on both switches in any leg of the inverter. This adds two redundant states to the switching combinations, meaning that one of these available states can be chosen in order to reduce

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the overall amount of commutations during a cycle. The maximum instantaneous absolute value of the line

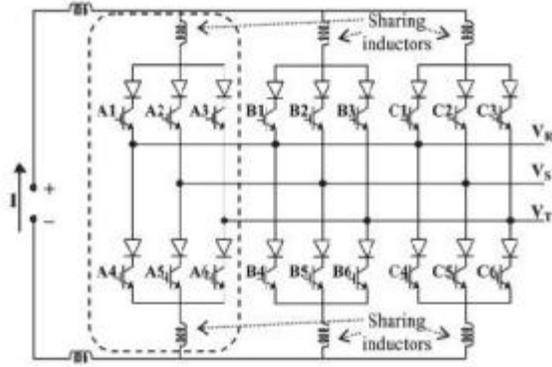


Fig. 2. Basic MCSI scheme.

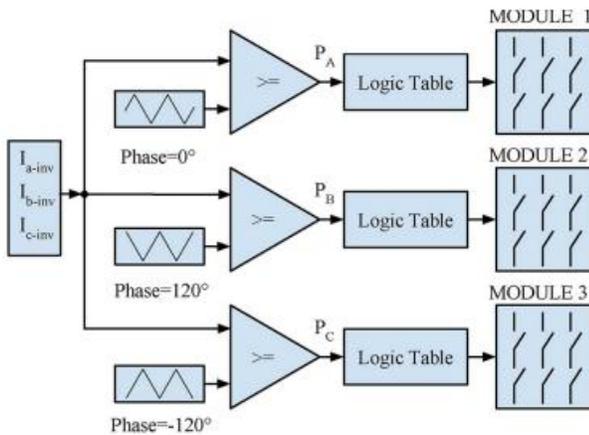


Fig. 3. Shifted carrier SPWM.

currents dictates which of the six switches is currently having the biggest ON time. Hence, if the zero state which utilizes that switch is chosen, the number of switch commutations in a cycle can be minimized, reducing power dissipation and increasing efficiency. In this way, every possible zero state is used during a complete cycle; therefore, an active algorithm is used to perform this enhanced zero-state selection.

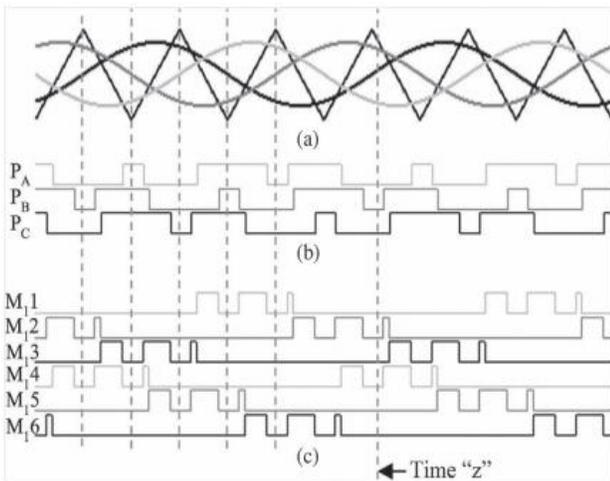


Fig. 4. Detail of the SPWM. Gate signals for one module.

The minimum voltage required by the MCSI to be able to inject current to the grid is

$$V_{\text{source}} = \frac{3\sqrt{3}}{2\sqrt{2}} m_a V_{\text{phase}} \cos(\phi) \quad (1)$$

Which is the result of equating input power with output power under an ideal no-loss condition.  $V_{\text{phase}}$  is the RMS phase voltage;  $m_a$  is the modulation index of the converter, ranging from 0 to 1; and  $\phi$  is the phase difference between the main voltage and the injected current. Although inductors are heavier and bulkier than capacitors, they have a higher mean time between failures (MTBF) and the failure mode is nonpolluting. Inductors can withstand high voltage ripple without losing performance, and their characteristics hardly suffer from degradation, provided that they remain within their operating temperature range. This implies safer inverters with longer MTBF, less maintenance requirements, and a lower risk of pollution. In addition, inductors built with high temperature superconductors will reduce losses appreciably, turning the MCSI into one of the most efficient solutions for multilevel inverters. In addition, implementation of fault tolerant topologies can be easily achieved by just adding a fourth module in a hot-spare configuration. Moreover, multilevel topologies present several advantages regarding total harmonic distortion (THD) and stress on power switches and inductors or capacitors. Thus, multilevel converters are preferred against the standard solution with three-level topologies in spite of the increasing complexity of the circuit and control.

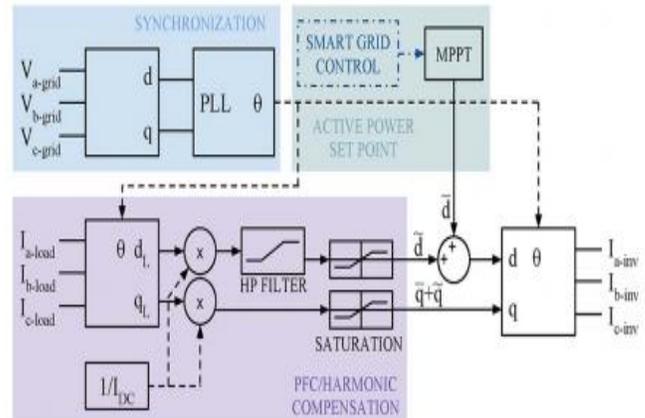


Fig. 5. Control scheme.

first-order dynamics is good enough. This allows drastically reducing the time required by simulations without affecting the overall behavior and accuracy of the model. Due to the nonlinear relation between the voltage and current provided by the cell, a power converter must be used to set the desired operating point.

### B. Control

The control block must fulfill five coordinated functions.

- Set the current drained from the cell to track the maximum power point of the cell stack (MPPT algorithm).
- Synchronize the MCSI with the grid.

- Generate the reference signals used for the modulation of the inverter Inv.
- Adjust the active power delivered to the grid.
- Compensate reactive power and harmonics in the grid.

The MCSI modulation scheme, power factor and harmonic compensation, phase-locked loop (PLL), and the MPPT controller are implemented in Simulink. The simulate algorithms in the MATLAB/Simulink environment without the need to write any hardware description language code. This allows quickly developing and testing the modulation logic and control algorithms while saving development time. The schematic of the developed control structure is shown in Fig. 5. To obtain the phase angle reference  $\theta$  using a PLL algorithm, first, the grid voltage is transformed from abc to dq0 reference frame using the Park transformation. The PLL is based on a fixed-point dual second-order generalized integrator PLL (DSOGI-PLL) as this implementation is one of the best solutions regarding setup time, steady-state error, and noise immunity. The phase angle reference  $\theta$  allows transforming the load currents from abc to dq0 reference frame. The load current in dq0 reference frame is then normalized to one by dividing the result of the Park transformation by the amount of dc current on the main inductor of the MCSI. This allows the modulation algorithm to work on a fixed scale, saving space and maximizing computing speed. The transformed components of the load current are  $dL$  (active) and  $qL$  (reactive). Hence,  $dL$  correlates with active power, and  $qL$  is proportional to the reactive power. A high-pass filter removes the dc component of the  $dL$  current, which is not necessary for the modulation of the MCSI. The mean value of the d reference current  $d^-$  is set by the MPPT or the smart grid control to supply active power to the grid.

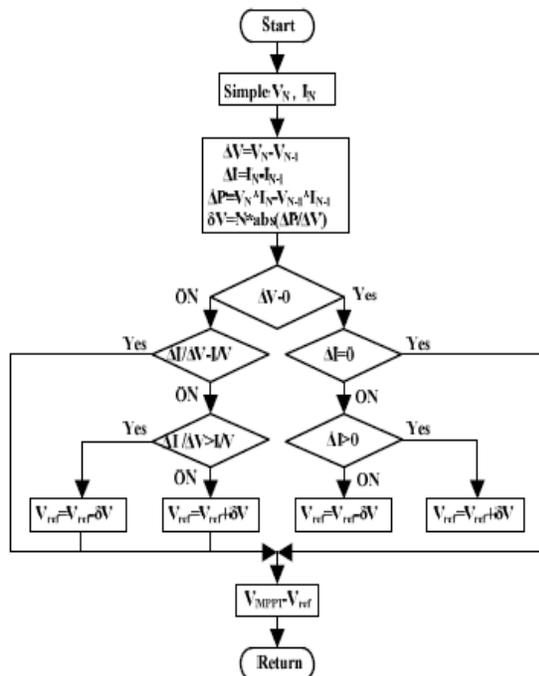


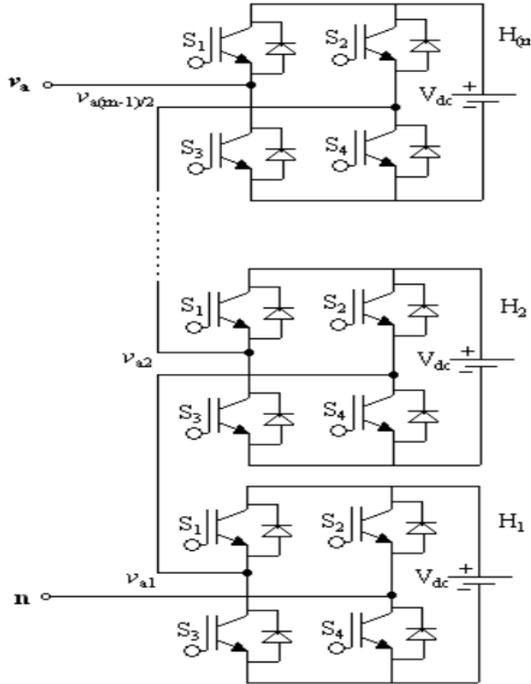
Fig. 6. MPPT algorithm.

To avoid saturation of the MCSI when entering in the over modulation region, the current signals are limited to the maximum amount that can be provided by the MCSI without significantly increasing distortion in the output current. Finally, these signals are anti transformed from dq0 back to the abc reference frame where they are used as reference signals for the modulation of the MCSI. The total active power the inverter supplies to the grid is composed of the active part of the harmonics present at the load plus the power provided by the fuel cell, which is controlled by the MPPT algorithm. The reactive power measured at the load is directly fed to the MCSI controller, accomplishing power factor and harmonic compensation on the grid caused by the load. The MPPT algorithm changes the active power reference of the system to track the maximum power point of the fuel cell in order to maximize the power delivered to the grid and increase the overall system performance. The MPPT is programmed in the Simulink with communication ports that allow a smart grid main control unit to adjust the amount of power delivered by the MCSI and the fuel cell in order to fit the operating conditions of the electric system, e.g. Reducing or increasing active power momentarily in a distributed generation system when a change in wind speed is detected. This feature allows improving the dynamic response of the electric grid maximizing power quality and safety. At startup, the main inductors of the inverter are discharged. To insure a soft start, the initial value of  $d^-$  is set to 1 in order to generate the least amount of zero states to reduce the speed of change on the current of the main inductors. As the inverter charges, the MPPT reduces the value of  $d^-$  to track the optimum power point of the fuel cell. The MPPT algorithm flow diagram, as shown in Fig. 6, is based on a perturb and observe algorithm. The derivatives of both power and current are calculated for each measurement, and based on the sign of these values, the  $d^-$  component is increased or decreased a fixed amount of 0.001 (0.1%) of the maximum current that the inverter can supply.

### C. Cascade Multilevel Inverter

The cascade multilevel inverter consists of a number of H-bridge inverter units with separate dc source for each unit and is connected in cascade or series. Each H-bridge can produce three different voltage levels: +Vdc, 0 and -Vdc by connecting the dc source to ac output side by different combinations of the four switches S1, S2, S3, and S4. The ac output of each H-bridge is connected in series such that the synthesized output voltage waveform is the sum of all of the individual H-bridge outputs as shown in Fig.7. By connecting sufficient number of H-bridges in cascade and using proper modulation scheme, a nearly sinusoidal output voltage waveform can be synthesized. The number of levels in the output phase voltage and line voltage are  $2s+1$  and  $4s+1$  respectively, where  $s$  is the number of H-bridges used per phase. For example, three H-bridges, five H-bridges and seven H-bridges per phase are required for 7-level, 9-level and multilevel inverter respectively. A typical waveform produced by 7-level CMLI. The magnitude of the ac output phase voltage is the sum of the voltages produced by H-bridges.

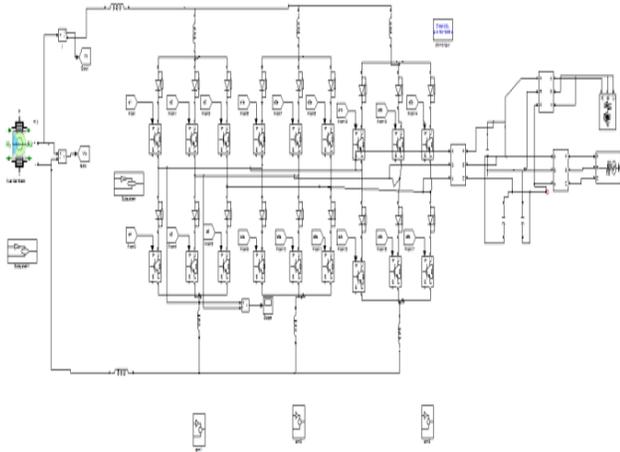
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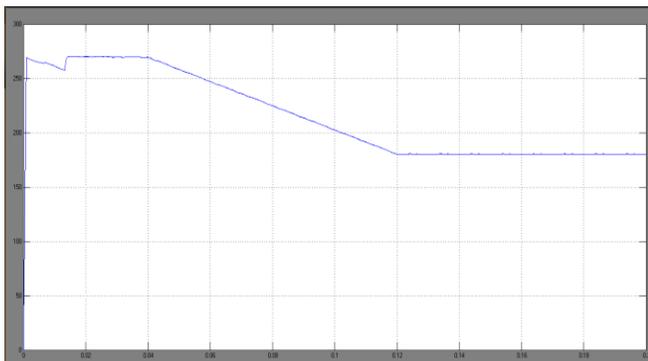
**Fig.7. Single-phase cascade multilevel inverter topology.**

**III. MATLAB/SIMULATION RESULTS**

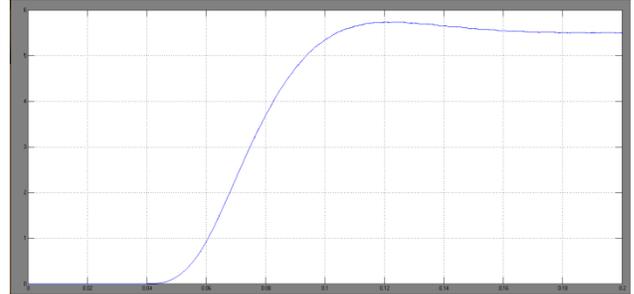
Simulation results of this paper is as shown in bellow Figs.8 to 15.



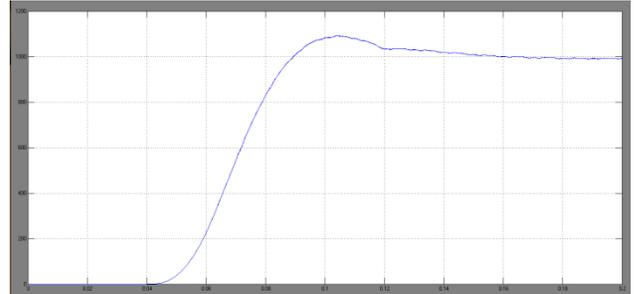
**Fig.8. Matlab/simulation circuit of the MCSI for seven level.**



**(a)**

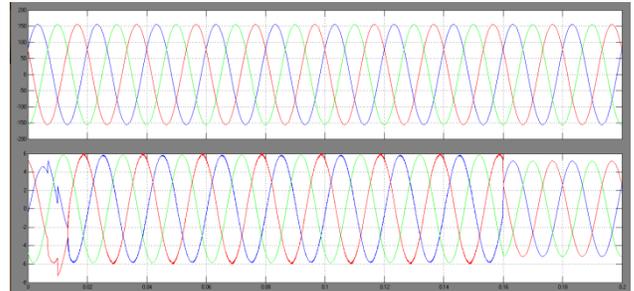


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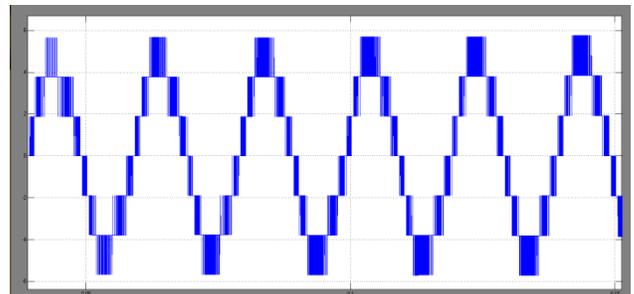


**(c)**

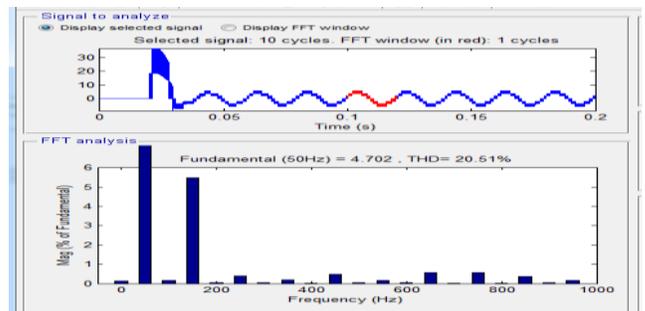
**Fig.9. Fuel cell voltage, current, power, and quadrature components of the current reference of the inverter.**



**Fig.10. simulation wave form of line voltage and line current at grid.**



**Fig.11. simulation wave form of seven level CSI.**



**Fig.12. Current THD for seven levels.**

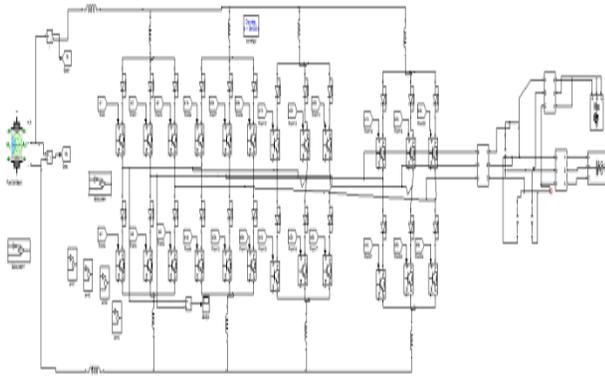


Fig.13. Matlab/simulation circuit of the MCSI for nine levels.

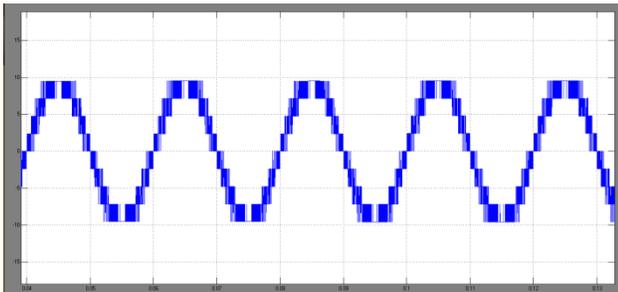


Fig.14. simulation wave form of nine level CSI.

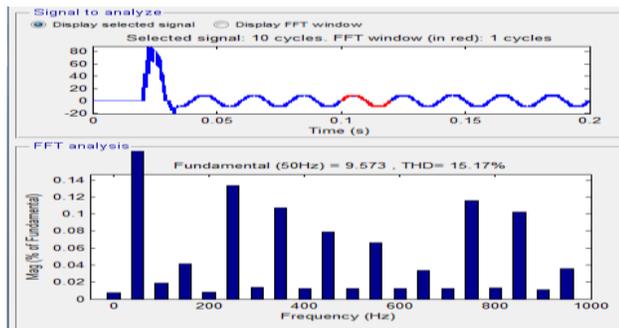


Fig.15. Current THD for nine levels.

#### IV. CONCLUSION

The behavior of a Nine-level three-module arrangement with distributed energy source was simulated, showing outstanding conditions of load regulation, linearity, and dynamic response. The topology adopted allows operation with high efficiency by reducing the current through the inductors and the losses in the switches. The dynamic response of the output current is satisfactory, both the steady-state and transient behaviors show no voltage spikes or current unbalances, and low-frequency current harmonics are reduced according to the structure implemented and the advanced switching method used; thus fully functional.

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