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PEM Fuel Cell Powered Multilevel Converter

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PAPER INFO

Paper history:
Received … … …
Received in revised form … … …
Accepted … … …

Keywords: FC, IBC, and NPC - MLC.

ABSTRACT

Nowadays, renewable energy sources are becoming further utilized to produce electricity. Fuel cell (FC) is one of the encouraging renewable and sustainable power resources as a result of its high power density and extremely low release. This paper presents suggestion and implementation of FC power system. So as to design a greatly efficient FC power system, proper DC - DC and DC - AC converters are needed. Among the different types of DC - DC converters, Interleaved Boost Converter (IBC) has been proposed as appropriate interface between FC and the next stage to transform the produced power energy (low voltage high current input into a high voltage low current output of the FC). 11-level Neutral Point Clamped (NPC) Multilevel Converter (MLC) is proposed for converting the DC output of the IBC to AC voltage to feed the load. MLC is chosen because it has many attractive features like high voltage capability, smaller or even no output filter, low voltage stress on load. Simulation of the proposed FC power system has been performed using MATLAB/SIMULINK..

1. Introduction:

The FC is one of the greatest promising renewable energy supplies and is gaining consideration by a lot of researchers. The research fields highlight on the power electronic converters associated with the FCs; to have a further effective conversion of power from the FCs to the load or to the grid [1]. FC systems have unregulated low voltage / high current output characteristics. For that reason, the output voltage of the FC need be stepped up by DC - DC converter. With regard to DC - DC converter types, the boost converter is counted since of its simplicity, low cost and great efficiency in addition to facilities of rising of the load voltage. The main challenge of constructing a boost converter for high power application is how to conduct the high current at the input and high voltage at the output. An IBC is appropriate applicant for current division among the phases of the converter and boosting the voltage on high power application. In addition to IBC has enhanced operation characteristics of higher power ability, modularity and improved dependability [1, 2, and 3].

The regulated DC output voltage of the IBC should be converted to an AC voltage and then the energy is directly supplies the load or injected to grid. MLCs are a relatively recent technology that is employed in such applications. Especially are compatible interested in the renewable energy resources field as numerous models of FCs, solar cells, wind - turbines, or micro-turbines can be coupled through a MLC to supply a load or the grid without voltage balancing challenges [4].

The MLCs are essentially categorized into three categories; are NPC - MLC, flying - capacitor MLC, and cascaded MLC. All the types have the similar property of improved the power quality, low switching losses, high voltage ability, and lowered (dv/dt) voltage stresses on the load.

Hence minor or even no output filter is needed. With the obtainability of high power rating semiconductor power switches, MLC is desirable for high power applications. The limitation of the MLC is that it required a great numbers of semiconductors components. Among three MLC topologies, NPC is the most common type of converter which is extensively used with the renewable energy sources [5, 6]. There are numerous sorts of multicarrier modulation techniques are utilized for controlling the NPC - MLC like: Phase Disposition (PD), Phase Opposition Disposition (POD), and Alternative Phase Opposition Disposition (APOD) [7]. This paper focuses on APOD method as it offers the lower THD as compared to the other two techniques [8]. Thus in this paper, 11- level NPC-MLC controlled by APOD is employed for the FC power system.

2. Proposed FC Power System:

In turn to have a more efficient conversion of power from the FC stack to the load, we will propose the two phase IBC in addition to 11 level NPC – MLC has the objective of transforming the power from the FC in an proper form. Block diagram of the FC power system is shown in figure 1. This system includes of a FC stack, two phase IBC, 11- level NPC - MLC and load.

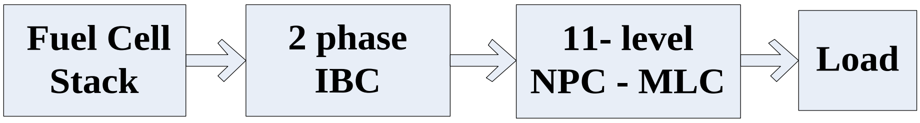

Figure 1. Block diagram of the proposed FC power system

2.1 FC Stack Model:

A FC is a static energy conversion tool that exchanges chemical energy of a hydrogen and an oxygen from air directly into electrical power with some heat and delivers water as its derivative. There are a lot of merits of operating FCs as a power supplies are as: (1) zero carbon emission, (2) It sustainable electrical energy, (3) A FC itself has no (few) moving parts (pumps and fans); consequently, it low audible noise, (4) FCs are modular; That is, FCs of varying sizes can be arranged together to meet a necessary power request. Regardless of their advantages, FCs have some drawbacks as well. As they are driven by chemical reactions, they have inherent delays that cause them to be lower in power density. Furthermore, they generate an inconstant voltage output when the load current changes rapidly [1, 9]

There are numerous kinds of FCs, which are described by the electrolyte applied. One of the greatest favorable is the small, fast switched on & off, low temperature operation (can be used at room temp.), light weight and comparatively easy to construct; is entitled Proton Exchange Membrane FC (PEMFC) (as well as called Polymer Electrolyte Membrane). So this type of FCs is employed in this work. The PEMFC involves of an electrolyte (protons conducting Polymer Membrane as electrolyte in PEM FC) between two electrodes (Anode & Cathode). The electrolyte lets the protons to pass through while obstructive the electrons. A graphic illustration of a PEM FC configuration is given in figure 2 [1, 10]

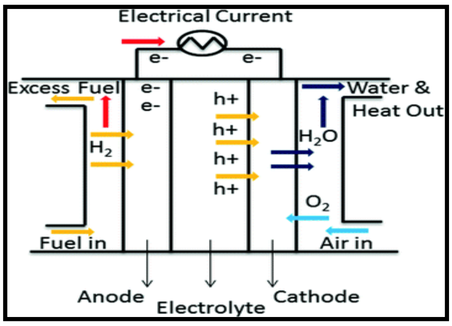

Figure 2. FC operation diagram

PEM FC electro-chemical procedure begins on the anode region where H_2 molecules are brought by flow plate channels. Anode catalyst partitions hydrogen on protons H^+ and electrons e^-; The protons H^+ passed to cathode through electrolyte, While the electrons e^- are travel to cathode over external electrical circuit (electricity is generated in this step) because the electrolyte doesn't allows the electrons e^- to passed through it. At the cathode hydrogen protons $H^+$and electrons e^- unite with oxygen O_2, to produce water and high temperature. Explained reactions can be stated by the next equations [9, 10]:

(anode reaction)

$$H_2 \rightarrow 2H^+ + 2e^- \quad \ldots\ldots\ldots\ldots \quad (1)$$

(Cathode reaction)

$$\frac{1}{2}O_2 + H^+ + 2e^- \rightarrow H_2O \quad \ldots\ldots\ldots\ldots \quad (2)$$

(General reaction)

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + heat + Electricity \ldots (3)$$

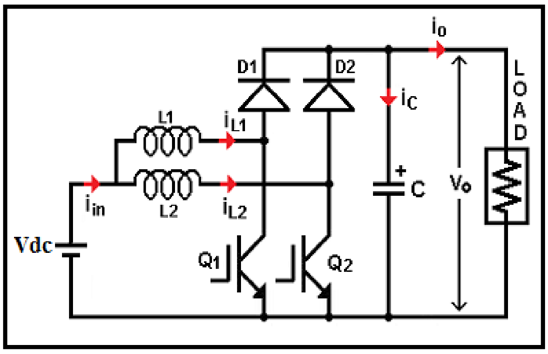

Figure 3. Schematic diagram of a 2 phase IBC

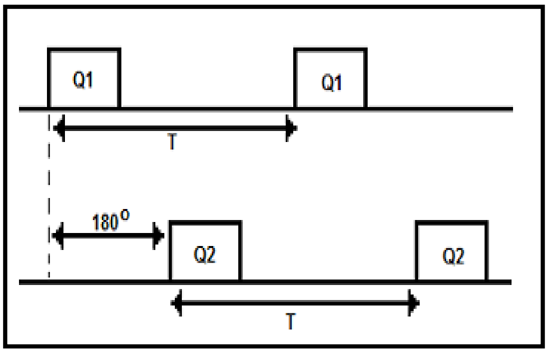

Figure 4. Timing diagram of control signals

2.2 Interleaved Boost Converter Model:

IBC typically used for renewable energy suppliers. It comprises of parallel combined of conventional DC - DC boost converter modules, the No. of inductor and power switch is equal to the No. of phases. On the other hand, the capacitor is common in as shown in Fig. 4, which are controlled by a phase - shifted switching function (interleaved action) [2].

To represent interleaving operation, Fig. 4 presents the timing diagram of control signals to the switches of a 2 phase IBC. Since this converter has two parallel units, the duty cycle for each unit is equal to $(V_{out} - V_{in})/V_{out}$. A phase shift should be realized between the timing signals of the first (master phase) and the next switches (slave phases). As there are two units parallel in this converter, the phase shift equal to 180° (i.e. the phase shifted equal to $360°/_N$ from the master phase, where N is the number of phase) [3].

As a consequence of interleaving action, IBC displays both lesser current ripple at the input side besides lower voltage ripple at the output side. So, the size and losses of the filtering stages can be decreased, and switching losses can be considerably reduced, therefore efficiency will increase. On the other hand the construction of IBC has more power switches and inductors than the traditional boost converters, which increases the complication of the converter. This is overcome by using coupled inductor in IBC which decreases the converter volume by using single core in place of two or more, to enhance the regulation of power converters [1, 2].

2.3 NPC - MLCs:

They are also known as Diode - Clamped MLCs. This topology gives the stepped output voltage through the usage of clamping diodes and power switches. Voltage stress across power devices reduces with the help of diodes. Single DC bus that is subdivided into a number of voltage levels by the series sequence of capacitors. To produce L' - level staircase output phase voltage (Vao, Vob): Common (L' - 1) DC side capacitors are needed, as (C1, C2, and C3) of the four level converter is shown in figure 5, (L' - 1) * (L'- 2) clamping diodes it should be used, 2 * (L' - 1) main switching devices are needed for each phase leg.

L-level staircase output line voltage (Vab) equal to (2 L' -1), then the seven level (L = 7) line voltage equivalent to four level (L' = 4) phase voltage for leg a plus leg b. Thus six diodes are used in each phase leg, and six of power switch and its parallel diodes are used in the 7-level NPC - MLC [6].

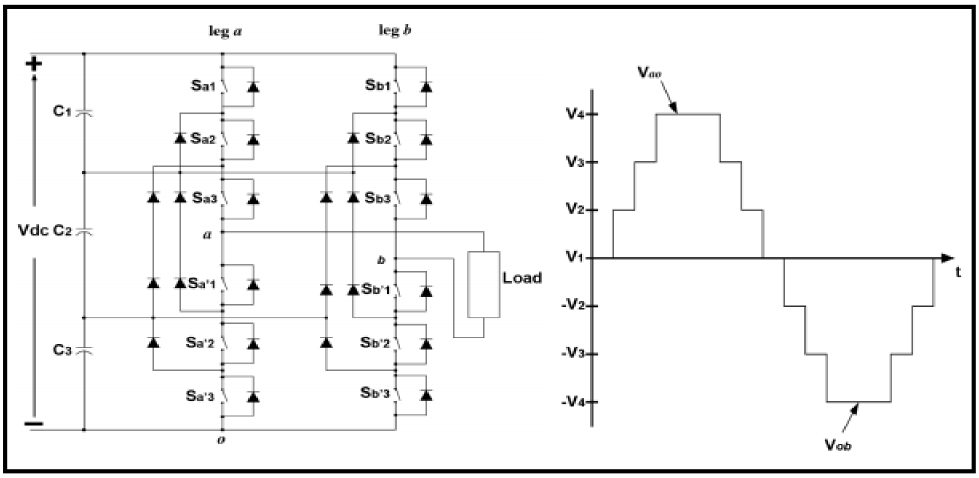

Figure 5. Seven – level NPC-MLC

2.4 APOD Control Technique:

For an L- level MLC, $L-1$ carriers with identical frequency and identical peak to peak amplitude. These carriers set are out of phase 180° alternately (i.e. for 5 - level MLC: 1st carrier is out of phase by 180° with regard to the 2nd, 3rd Carrier is out of phase by 180° with respect to 2nd carrier. Whole APOD control technique arrangement for 5 - level MLC with 4 carriers as presented in figure 6). The unique reference waveform is always compared with all of the carrier signals. If the reference is greater than the carrier signal, the active device that corresponds to that carrier is switched on and vice versa [8, 11].

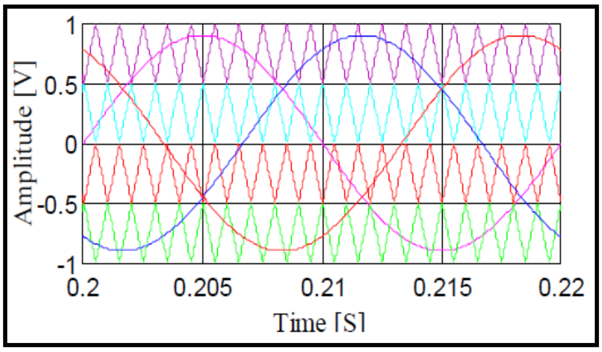

Figure 6. APOD Control Technique

3. Simulation Circuit:

To verify the proposed schemes, the simulation of the proposed FC power system is implemented by using Matlab/Simulink simulation tool, is shown in figure 7.

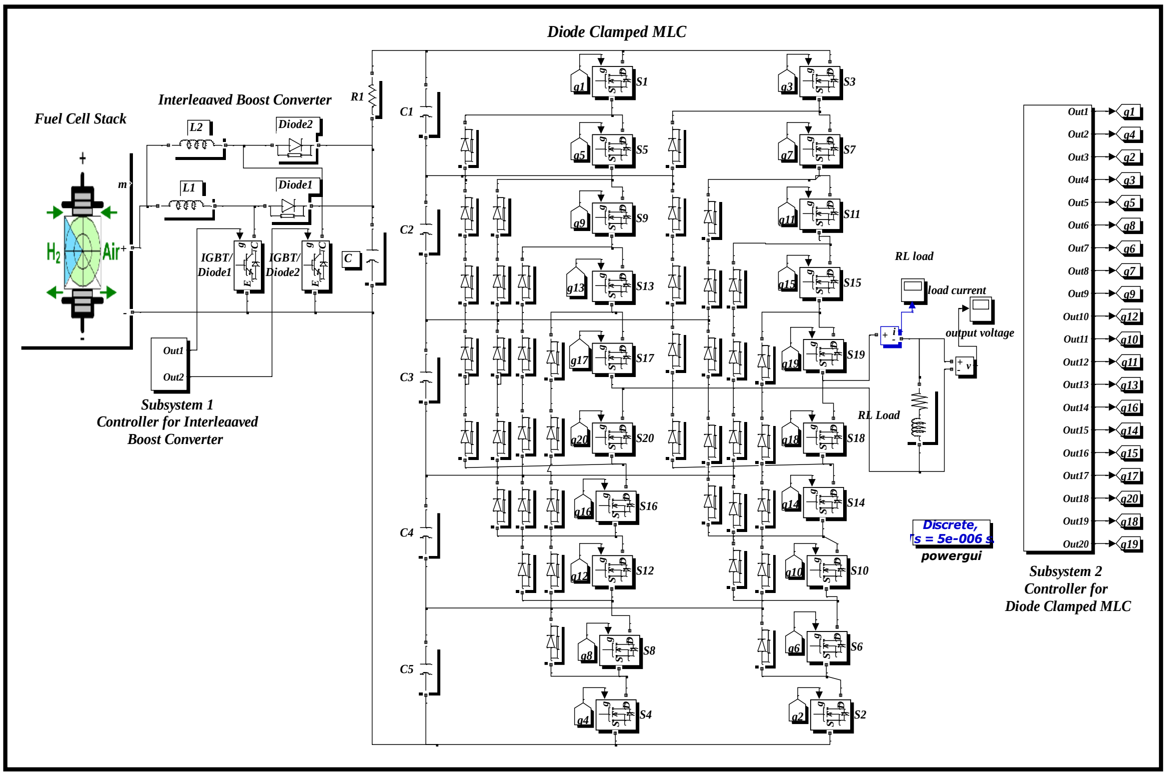

Figure 7. Simulink diagram of the proposed FC power system model

It appears the Simulink block diagram of the FC power system consists of five parts:

i. **FC stack:** a case study of 6 KW PEM FC which has the parameter as shown in Table 1(a) is adopted.

Table 1: FC parameters

Parameters	Values
Rated power of stack	6 KW
Open circuit voltage	65 V
Nominal voltage	45 V
Nominal current	133.3 A
No. of cells	65
Nominal stack efficiency	55 %
Operating temperature	65°

ii. **BC:** Table 2 enlists the main components of inductor and capacitor values for IBC.

Table 2: IBC parameters

Parameters	Values
Current ripple	1A
Voltage ripple	5 V
Switching frequency	10 KHZ
L	7 mH
C	150 µF

iii. **Controller for IBC (Subsystem 1):** The terminal voltage of FC is controlled by varying of DC-DC converter duty cycle. This controller is shown in figure 8.

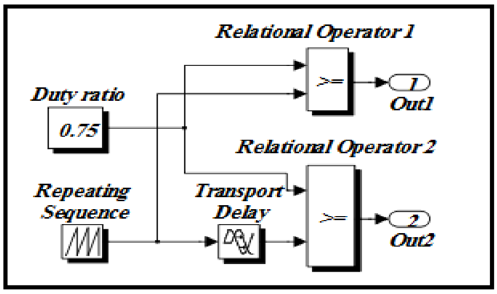

Figure 8. Subsystem 1 (Controller for IBC)

iv. **11-Level NPC MLC** with RL load (10 Ω, 3 mH): Table 3 enlists the component requirements for 11 level MLC.

Table 3: 11-Level NPC- MLC specification

Type of MLC	NPC
Main switching devises	20
Main diodes	20
Clamping diodes	40
Balancing capacitors	5

v. **Controller for NPC- MLC:** For implementing the APOD control technique for 11-level NPC MLC (see Subsystem 2, figure 9), 10 - carrier signals with the same peak to peak and same switching frequency are required. Each carrier of this technique is phase shifted by 180° from its nearby one. These eight signals are compared with single reference sine wave to produce eight signals for the first leg of the converters and then are negated to produce the second eight signals for the second leg of the converters.

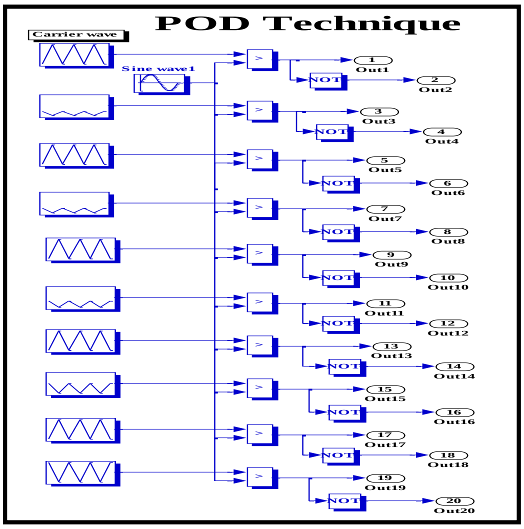

Figure 9. Subsystem 2 (Controller for 11-Level NPC MLC)

4. Simulation Results:

Figures 10 and11 show the output voltage waveform and the load current of IBC and are around 265V, 10A.

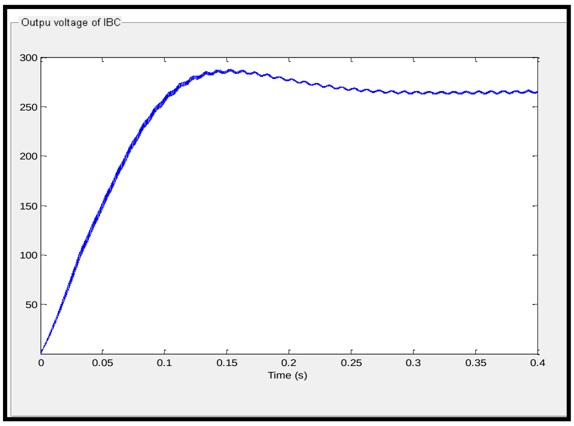

Figure 10. Output voltage waveform for IBC

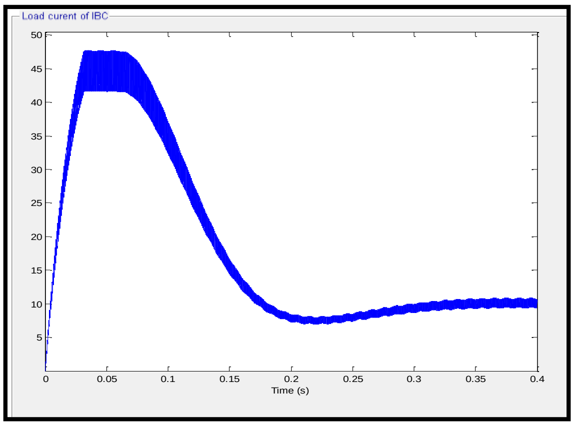

Figure 11. Load current waveform of IBC

The output voltage and current waveforms with its harmonic spectrum analysis for 11-NPC MLC interfaced with the FC - IBC are shown in figures 12-13.

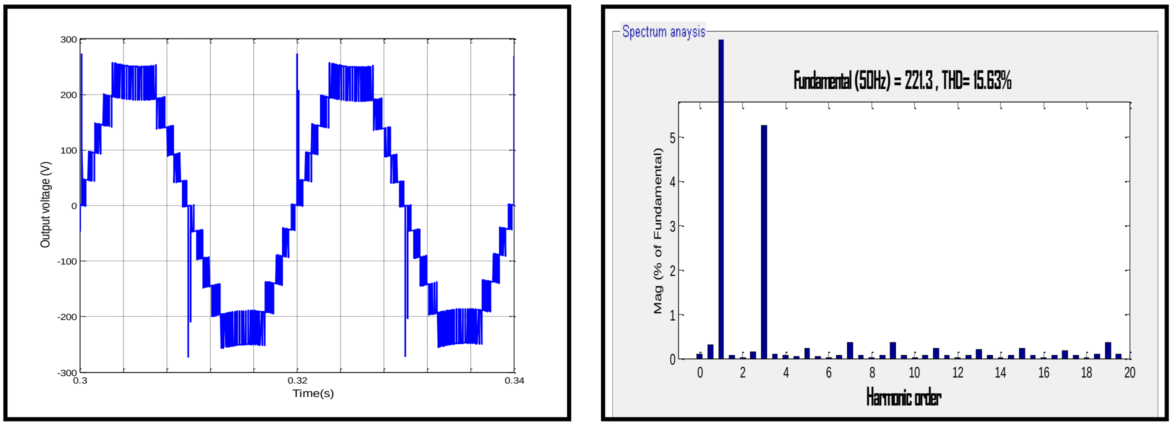

Figure 12. Output voltage waveform and its harmonics spectrum analysis of the MLC

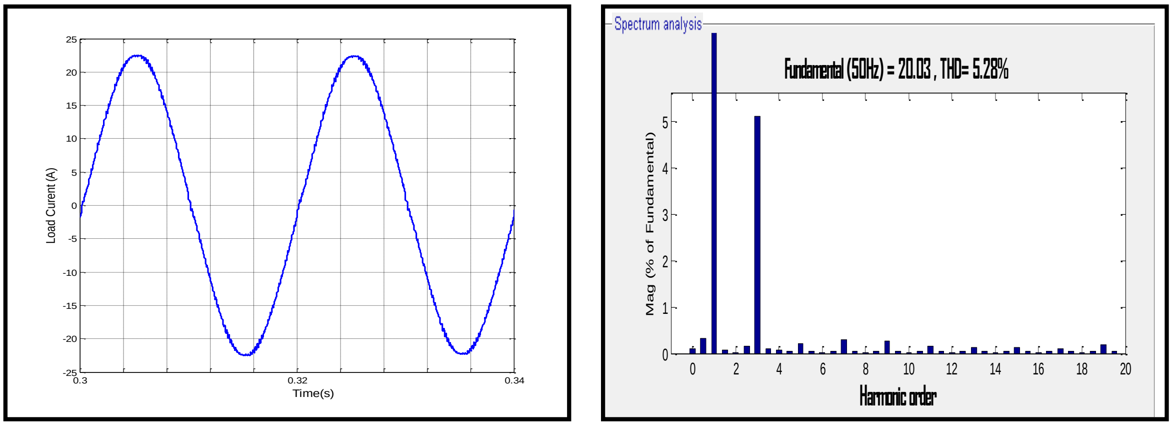

Figure 13. Load current waveform and its harmonics spectrum analysis of the NPC – MLC

The AC output voltage of the 11- level NPC - MLC is around $220V_{rms}$ with low THD, and it equal to 15.63, and the load current is around 20A with THD value equal to 5.28 which is in the acceptable level. The harmonic content of the NPC – MLC is proportionate with the numbers of level of the MLC, so it's possible to improvement the harmonic content by increasing the levels of the converter.

5. Conclusions:

This paper designed FC power system, the system is consist of a PEM FC as a renewable energy source and power electronic converters for supplying the load, the converters involved 2-phase IBC combined with 11-Level NPC - MLC. The simulation of the system was successfully carried out using MATLAB Simulink software and the obtained waveforms were observed. It's distinguished that the harmonics in the output voltage waveform was reduced significantly by applying the configuration of multicarrier modulation technique (APOD technique), and this means that there is no need to a high necessity filters. It's possible to improve the and power capability beside its quality of the system by increasing the number of phases of IBC and the number of levels of NPC-MLC, but this improvement is accomplished with increasing the number of power electronics component besides the control circuit is complicated. Thus the designing the power converter should be realized according to requirements of the application.

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الخلاصة :

في الوقت الحاضر، أصبحت مصادر الطاقة المتجددة أكثر استخداما لتوليد الطاقة الكهربائية. تعتبر خلايا الوقود احدى مصادر الطاقة المتجددة والمستدامة الواعدة بسبب الطاقة العالية الصادرة منها فضلا عن قلة المخلفات البيئية الناتجة عنها. لغرض تصميم وتنفيذ منظومة خلية وقود عالية الكفاءة فانه يتطلب استخدام مقطع تيارمستمر DC - DC ومغير قدرة DC - AC مناسبان. ومن بين الانواع المختلفة لمقطعات التيار المستمر تم اقتراح استخدام مقطع التيار المستمر المتداخل الرافع متعدد المراحل Interleaved Boost Converter كدائرة مناسبة لربط خلية الوقود بمغير القدرة لغرض تحويل اخراج خلية الوقود ذو التيار العالي والفولتية الواطئة الى قدرة خارجة ذو تيار واطئ وفولتية عالية. أما لتحويل الفولتية المستمرة الخارجة من مقطع التيار المستمر الرافع متعدد المراحل الى فولتية متناوبة لتغذية الحمل فقد تم استخدام مغير قدرة دايودي متعدد المستويات Multilevel Converter بسبب ميزاته المتمثلة بقابليته على العمل بفولتية عالية ذو جودة عالية من حيث عدم احتوئها على توافقيات غير مرغوب بها وبالتالي عدم الحاجة الى المرشحات. تم تمثيل منظومة خلايا الوقود المقترحة برمجيا باستخدام الماتلاب.