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Five-Level Reduced-Switch-Count Boost PFC Rectifier with Intelligent Controller

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Abstract

A five-level Power Factor Correction incremental rectifier (PFC) is proposed in this paper. In this topology, the output voltage and current of the rectifier are controlled using the multilevel modulation and smart controller technologies. A multi-carrier pulse width modulation is used to create the switching pulse. In this topology, the number of semiconductor switches is reduced to 3. The smart controller is implemented using a Multilayer Perceptron (MLP) neural network and it is trained using the backpropagation algorithm. This controller is used instead of the well-known PID controller to control the input voltage and current. It should be noted that in this work, the goal is to design an intelligent controller using a neural network instead of a PID controller. The results obtained using this controller as compared to the PID controller show a decrease in the peak voltage, an increase in the rise time, and a ripple reduction in the output voltage. This study is conducted using the Simulink environment in MATLAB and the results suggest that a smart controller can be an alternative to the PID controller.

***Keywords**: five-level rectifier, multi-carrier pulse width modulation, perceptron neural network, smart controller.*

1. Introduction

The smart algorithms such as the genetic algorithm, particle swarm optimization algorithm, and the backpropagation algorithm are used to tune the PID controller parameters including the proportional gain k_p, integral gain k_i, and derivative gain k_d coefficients. These parameters are calculated to obtain a closed-loop system output for the step response that is considered satisfactory. Factors determining the step response include the rise time, the settlement time, the maximum peak, and the steady-state error. It is possible to obtain an acceptable and proper value by tuning the PID controller parameters. The K_d, K_i, and K_p coefficients can be calculated using the well-known Ziegler–Nichols method when the PID controller is used. This method highly suits linear systems and the parameters can be improved through trial and error [1].

The linearization of a nonlinear system to obtain a differential equation showing the input-output relation is complicated. In these cases, the numerical and qualitative calculation methods such as the genetic algorithm and fuzzy logic can solve this problem. Therefore, designers only have to determine the desirable definitive response for the output and input. Next, data is put into a neural network and the network is trained using the proper algorithm. The results of experiments conducted through different processes suggest that the achievements obtained through the smart algorithms may offer a better response than the classic Ziegler–Nichols method. Besides, the smart algorithm can adjust systems that cannot be used with classic rules. Examples of these systems are nonlinear and complex systems [2]. A neural network is introduced in the following to implement a controller using a PID controller and a neural network that can be used in the design of nonlinear and complex systems.

Fuzzy controllers generally derive a control strategy from the language rules, which are converted into mathematical terms using the fuzzy sets and fuzzy logic concepts [1]. Neural networks are capable of learning systems' behaviors based on the information on the systems' outputs and inputs [2]. Both the fuzzy and neural controllers are also useful especially in controlling complex systems [2, 3].

Optimization generally refers to a set of methods and techniques used to calculate the minimum and maximum values of mathematic functions including the linear and nonlinear functions. The optimization methods are classified into two categories: evolutionary separation and gradient-based methods. Numerous methods have been developed to annul traditional gradient-based optimization methods due to scientific and technological advances.

The following considerations have to be taken into account in this section.

1. The network input data is designed for neural network error training. This error originates from the input and output.
2. The designed network has one input, ten hidden layers, and one output.
3. Simulations are carried out in MATLAB using the neural network toolbox.
4. The neural network training method is based on the sum of square errors, which is expressed via equation (1).

$$F = \frac{1}{n}\sum_{i=1}^{n} e_i^2 = \frac{1}{n}\sum_{i=1}^{n}(t_i - a_i)^2 \qquad (1)$$

In equation (1), (*n*) denotes the number of tested samples, (*ti*) is the neural network output, and (a_i) represents the actual and available outputs. [1-3]

In this paper, a five-level power factor correction rectifier (PFC) controlled by multilevel modulation technology and intelligent controller is reported. The input voltage wave form is five-level quasi sine wave without coupling to the capacitor. The rectifier generates a constant DC voltage at the output. Multi-carrier pulse width modulation has been used to create pulse switches.

In this topology, compared to a full-bridge rectifier, the number of active switches has been reduced to three. Intelligent controller implemented by multi-layer perceptron (MLP) neural network and trained by the post-propagation algorithm is employed to control the input AC current and output DC voltage. Simulations are conducted in MATLAB-SIMULINK and results are shown and discussed. Various changes are applied on the running system to validate the good dynamic performance of the designed controller. This paper shows that the smart controller can be an alternative to the conventional PID regulators.

High power factor or PFC boost converters are among the most widely used devices in the industry. The main concerns of such inverters are the unity power factor and a low harmonic distortion of the input waveforms, which can be ensured by generating a DC voltage which is higher than the amplitude of the mains peak voltage, whereby switching devices become unavoidable[4,5].

There are various converters such as SEPIC [6], Cuk [7] and Buck-Boost Converters [8, 9]. These converters have lower bass voltages compared to other types of converters called boost. On the other hand, the voltage and current stress on the semiconductors are higher, which increases switching and conduction losses. Therefore, these structures are not suitable for high power supplies. There are no problems in Boost converters and they are widely used in the applications of PFC.

Traditional boost converters are the least efficient with increasing ripple current of the inductor and high turn-off current. Cascading and interconnecting the boost converter is done to reach the high voltage but requires many components, which results in increased cost and reduced performance [10, 11].

High voltage regulation can be achieved by increasing the turn ratio of the coupled inductor, but it requires an auxiliary circuit to reduce the peak voltage [12, 13].

Multi-level transducers increase Gain voltage but reduce reliability and increase the number of switches [14].

In [15], a five-level PFC rectifier that reduced the number of active switches rectifiers presented. A cascaded PI controller was designed to regulate and ensure the output DC voltage unit power factor mode of AC input voltage and current. In addition, a low harmonic AC waveform is generated achieved through the implemented controller and use of a small inductive filter on the input line. One of the main topics of switching rectifiers is the high switching frequency that has reduced in this work with PWM technique by adoption of a multi-carrier modulation scheme. In addition, DC capacitor center was not connected to the load had to share the load to provide a neutral point [16].

In [17], a novel single-phase active five-level rectifier for integrated EV battery chargers is presented. Because it generates five different voltage levels and allows you to reduce the values of passive filters used to connect to the grid.

In [18], Fault Tolerant (FT) is main goal. The proposed topology eliminates the need for two-way switches, which are commonly used in commonly used methods. In addition, the proposed topology preserves system performance in operations for errors, as is normally the case. In addition, the proposed FT topology maintains inverter performance at similar output rates and uninterrupted inverter performance.

A new switching frequency control strategy has been proposed in [19], which has been proposed to improve an improved five-level active rectifier (IFLAR). Constant switching frequency operation is a great advantage since the generated harmonic range is well known and it is possible to design passive filters to reduce such harmonics.

In [20], presents a new topology of a multi-level PFC converter. The proposed DC link splitter topology can produce five separate voltage levels with a reduced number of power devices.

Authors in [21] presented a comprehensive study on Five-Level Packed U-Cell inverter called PUC5. The main advantage of the PUC5 topology over other common multilevel systems is the redundant switching states, which facilitate the voltage compensation of the flying capacitor in its configuration. The switching state of the PUC5 inverter is analyzed to ensure even voltage equalization [22].

Various authors have worked on different concepts and parts of PFC and improving its parameters. For example, authors in [26] combined the advantages of FC converters as the use of lower voltage-rating devices, natural balancing FC voltages, and good loss distribution among the switching devices. Or in [27], is presented a converter with simple structure and control, low component count, and inrush current handling capabilities. For another example, authors in [28] presented a topology with very low input current THD, that could well supplement in aircraft, portable or distributed generation applications, modern high-speed permanent magnet synchronous generators featuring a quite small stator impedance. But none of them don't work on ANN and Intelligent Controller about them. Using neural networks, you can have intelligent controls on various devices, such as [29-31], which uses the neural network to control FACTS devices.

In this paper, a multilayer neural network is trained on a nonlinear closed-loop control system with a sinusoidal input, which leads to system optimization. Section 2 presents the rectifier model and the design of the related modulation in [15]. In section 3, the notions and the method of training the smart controller and the PID controller are discussed, while section 4 presents the results of simulations and comparison of the smart controller with the PID controller. Finally, a summary is provided in section 5.

2. Five-Level Reduced-Switch-Count Rectifier Circuit

In Fig. 1, a five-level rectifier circuit with three switches and 6 diodes is depicted. As seen, a double-throw switch is used. The switching technique is also presented in Table 1.

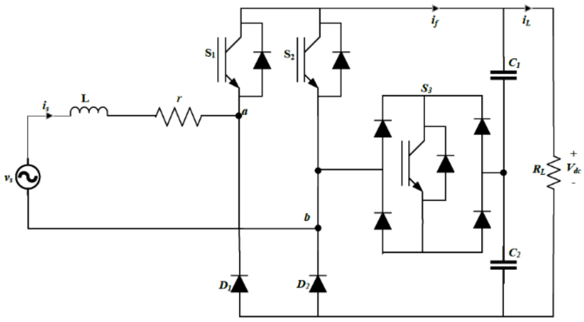

Fig. 1: The five-level rectifier [15].

If the current is positive, turning on switch S1 conducts diode D_2. Therefore, V_{dc} is manifested in V_b and both the capacitors (C_1 and C_2) are charged. In the next switching state, a low-impedance current path is provided via capacitor C_1 and the *S3* double throw switch by simultaneously turning switches S_1 and S_3 on. Hence, the upper capacitor is charged and the voltage changes to$+\frac{Vdc}{2}$. Level zero is created by a short circuit between points *a* and *b* using switches S_1 and S_2. Regarding the direction of the negative current, diode D_1 is in charge of the passage of the required current. When S_3 is turned on in the current path, the current only passes through capacitor C_2. When D_1 is conducted, voltage $-\frac{Vdc}{2}$ is created in the rectifier input. Finally, when the current is negative, if S_2 is turned off, diode D_1 is turned on and V_{ab} equals to $-V_{dc}$. The lack of another switching mode is the most important concern in this topology, and implementation of the control circuit optimizes switching.

Table 1. The switching modes in the five-level rectifier [15].

Switching states	i_s	S_1	S_2	S_3	V_{ab}
1	>0	1	0	0	$+V_{dc}$
2	>0	1	0	1	$+V_{dc}/2$
3	≥0 & ≤0	1	1	0	0
4	<0	0	0	1	$-V_{dc}/2$
5	<0	0	1	0	$-V_{dc}$

3. Details of Proposed Method

3.1 The Proposed Control Circuit and Switching Techniques

The PWM is useful for pulse generation and preservation of a low, fixed, and practical switching frequency with industrial high power. As seen in Fig.2, four carriers (Cr_1, Cr_2, Cr_3, and Cr_4), which represent a triangle wave, are used for the modulation of the reference signal. Each carrier is in charge of generating pulses for the alternating voltage level and the switching mode, which is indicated by logical blocks. The pulses associated with three switches, which are depicted in Fig.1, are also applied [1]. This topology is also used for switching in this paper.

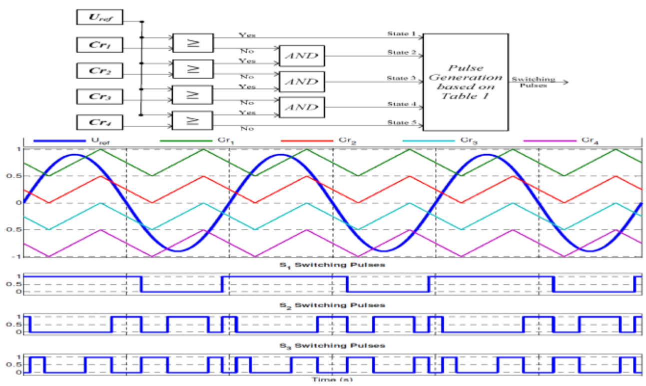

Fig.2: Multi-carrier PWM modulation at a low and fixed switching frequency [15].

It is possible to turn the grid current into a sine wave through current control but the switching problems such as the high and variable switching frequency result in the complications and increased losses in the hardware installation process.

In Article [15], a simple controller consisting of two cascade loops (*i.e*. the outer loop regulates the voltage and the inner loop controls the current) is used to create a rectifier topology that is useful and has industrial applications. Fig.4 shows the implementation of the controller. Equations 2 to 5 also express the calculation procedure and the transfer functions.

In Eq. (2), *L* denotes the line inductance and *r* represents the parasitic resistance of the line inductance. Besides, the coefficient α shows the rectifier slew rate. Eq. (2) is taken to the Laplace domain and it is connected in series to a PI controller (*Hc(S)*) to create the inner closed-loop controller (Fig. 3).

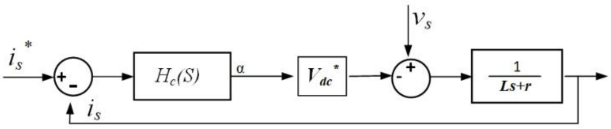

Fig.3: The inner loop of the designed controller [15].

K shows the average value of the slew rate constant, which is determined by the current in the i_c capacitor and the value of *c* equals C_1 and C_2. The outer loop of the rectifier is designed by taking eq.3 to the Laplace domain and placing a PI controller, which is shown by *Hv(s)* in Fig. 4.

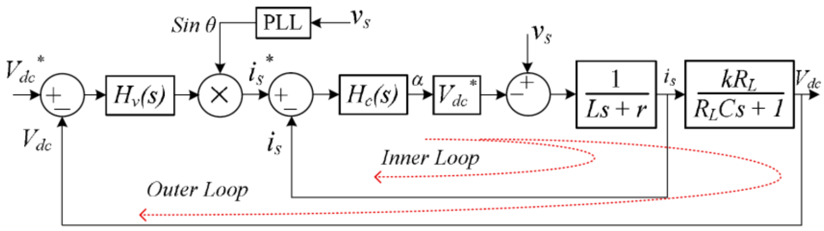

Fig.4: The cascade control block designed for the 5-level rectifier [15].

In this paper, the inner PID controller (*Hc(s)*) is replaced with a smart controller trained using the backpropagation algorithm. This controller is described in the following.

3.2 Neural Network

The structure of the artificial neural network model is inspired by biological neurons. Some of the characteristics of the biological neurons include nonlinearity, simplicity of the calculation of units, and the learning capacities. In an artificial neuron, the weight of each input value is affected and the performance of this weight is similar to a synaptic connection in natural neurons. These processor elements consist of two sections: the first section contains the input overweight and the second part is a nonlinear filter called the “neuron active function”. This function compresses the output [23-25].

In this work, a multilayer perceptron network with an input, an output, and ten hidden layers is used. The characteristics of the artificial neural networks include their ability to learn information, dispersion, generalization, parallel processing, and resistance. Fig.5 shows the neural network model used. In fig.5, the branches between the neurons, W_{ij}, represent the network weight [23-25].

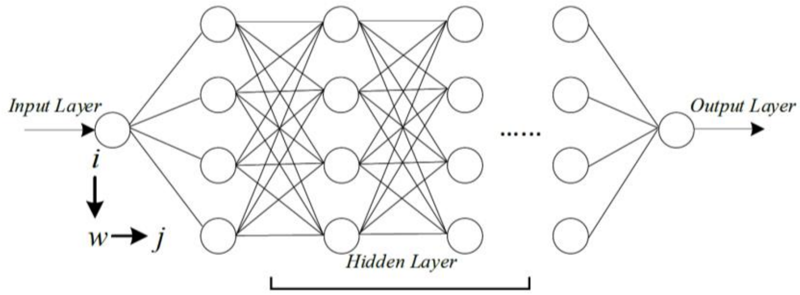

Fig.5: The multilayer perceptron neural network model [23].

Various models of training a neural network are available. In this paper, the backpropagation method is used for the perceptron neural network. After training the neural network, the *Hc(s)* PID current controller in Fig.4 is replaced with this network as the controller. The simulation results are also presented in section 4. The results of simulations are compared to the results reported in [15] and it is indicated that the smart controller performance is partly better than the PID controller. It is worth stating that this topology is a new alternative to the PID controller.

3.3 Training the Back Propagation Learning Algorithm

Fig.6 depicts the process of training the multilayer neural network with the backpropagation algorithm. In this case, first, the network weights are allocated randomly. Thereafter, the desired input is applied to the network. The resulting output is also compared to the target output. The error resulting from this process results in changes in the network weights. This process is iterated until the error is minimized. Thereafter, network training is completed. It is also worth noting that the error is never zero.

As seen in fig.7, first, the input and output data is received from a PID controller to train the neural network. This data can be provided with the desirable input load, output load, and voltage values. In this paper, the input voltage is Vs=170 alternating voltage and the output voltage is $V0$=200 direct voltage. The load is also RL=80. It is worth noting that network training is carried out only using these input and output parameters. After training the network and placing it in the controller system, if the system parameters in the inlet (including the alternating input voltage) and the outlet (including the direct output voltage and the system load) are changed, the performance of the smart control system is stabilized.

The required data (i.e. the output and errors) is obtained within a short period, e.g. 10 seconds. Afterward, this data is given to the MLP (multilayer perceptron) neural network, which has 1 input, 1 output, and 10 hidden layers, to be trained. After training, the PID current controller is shown in fig.4 (See fig. 8). Next, the test is repeated for different loads and load voltages, and the results of the test along with the comparison with the test results in [1] are presented in the following section.

In many articles, the genetic algorithm, the particle swarm optimization algorithm, and the backpropagation algorithm are used to calculate the PID controller coefficients. In all the studies, all the systems were linear and their input was a step function. It could be, therefore, stated that this research is the first study conducted on the replacement of

PID controllers with smart controllers. In this work, the PID controller parameters including *Kd*, Ki, and *Kp* are not calculated. Rather, the PID controller is designed and replaced. The smart controller can be used in a fully nonlinear system such as the rectifiers, inverters, and converters, which is a novel idea.

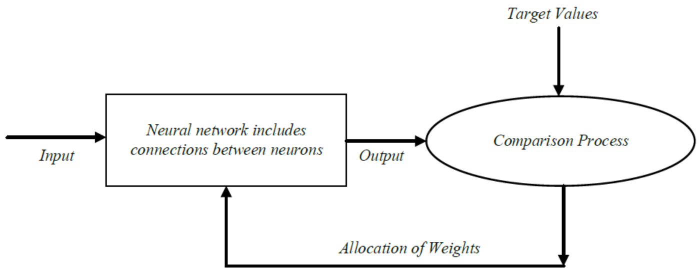

Fig.6: The process of training the backpropagation algorithm.

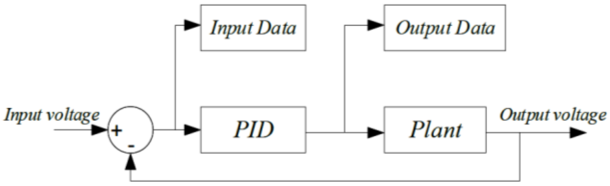

Fig.7: The calculation of data through the MATLAB simulation.

Fig.8: Implementation of the system with a smart controller.

4. Simulation and Comparison Results

In this work, the dynamic performance of the proposed rectifier, the control technique, and the implemented modulation is analyzed using the MATLAB/nftool simulator and the parameters listed in Table (2).

The Fixed Step Discrete simulation mode is selected and the sampling time is set to 20 µs. As a result, the controller can be used in real-time. The simulation parameters include the input impressed voltage, which is 170 alternating voltage, and the capacity of the filter capacities, which is 1000 *microfarad/load*, and the inductor capacity is 2.5 *mH*. The simulation parameters are listed in Table (2).

Table 2. The system parameters

AC Grid Voltage	170 V V_{max}
AC Grid Frequency	60 Hz
DC voltages (V_{dc})	200 V
DC Capacitor (C1 & C2)	1000 µF
DC Load (RL)	80 ohm and 40ohm
Interface Inductor	2.5 *mH*
Switching Frequency	5 kHz

First, the system response is analyzed in the stead and fixed state. Fig.9a shows the input impressed voltage which is alternating voltage and equals 170V. Fig.9b shows the circuit input current waveform, which is fully sinusoidal. As a result, the distortion is minimized in the input. Fig.9c shows the circuit output voltage, which is 200 direct voltage. As seen, the voltage ripple in the output is highly insignificant. Fig.9d shows the load power factor, which eq. 1. Fig.9e also shows the input voltage wave of the rectifier, which has 5 levels. As this waveform becomes more similar to the sine wave, the Total Harmonic Distortion (THD) decreases in the input, which reduces distortion in the input voltage. Fig.9f shows the output current waveform, which is 2.5 ampere.

System stability in the sudden variations resulting from the output load or changes in the input impressed voltage is discussed in the following. Besides, the output direct voltage is changed for the desired value and system performance is analyzed.

In fig.10, the waveforms of the input current, the output current and voltage, capacitors' voltage, and the power coefficient are shown for a 50% sudden change in the output load. When the timer shows "3 seconds" the output load decreases from 80 Ω to 40 Ω. As seen, in fig.11, the system is stabilized immediately without any overshoot. It is also worth mentioning that the network is trained for a constant load of 80 Ω, a constant voltage of 200V in the output, and a voltage of 170V in the input. In this case, it provides a stable and satisfactory response for a 50% change in the load.

For a 30% change in the input impressed voltage, the system waveforms are depicted in the following in Fig.11. As seen, the smart controller effectively responds to this change, stability is not observed in the system and the proper response is created in the output. Besides, the output voltage remains unchanged at 200V for an 80-ohm load.

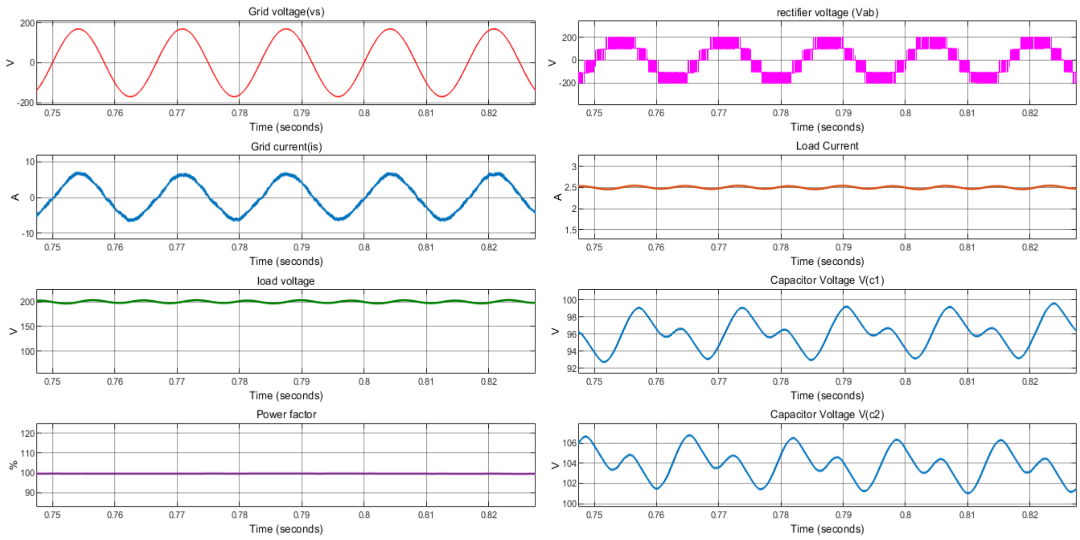

Fig.9. Results of the rectifier simulation using the smart controller.

Since the given rectifier is capable of changing the output voltage and it can function as a boost converter, it changes the output voltage from 200V to 250 direct voltage. It also examines the system response under the 80-ohm load and input impressed voltage of 170V. Fig.12 presents the smart controller performance in a stable state. Within 3 seconds, this change is applied through stepped variations. In Fig.12a, the input impressed voltage does not change. In Fig.12b, the input current undergoes distortion at the second 0.1 and then it reaches the stable state. As seen in section C of fig.12, the output voltage reaches the stable state after 0.1 seconds and the overshoot. Also, in section H of fig.12, the voltage waveform in the rectifier input is stable and it lacks distortion. The stability of the output current waveform is shown in fig.12 similar to the output voltage after an overshoot.

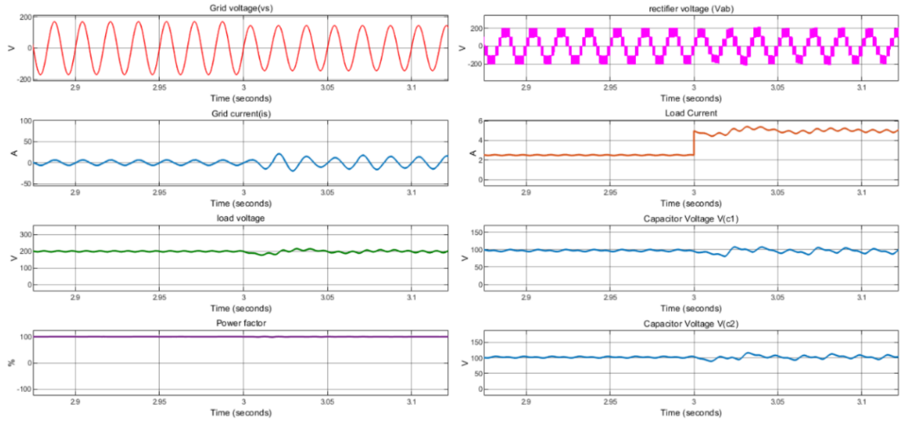

Fig.10: Simulation resulting during the decrease in the load from 80 Ω to 40 Ω with the proposed method.

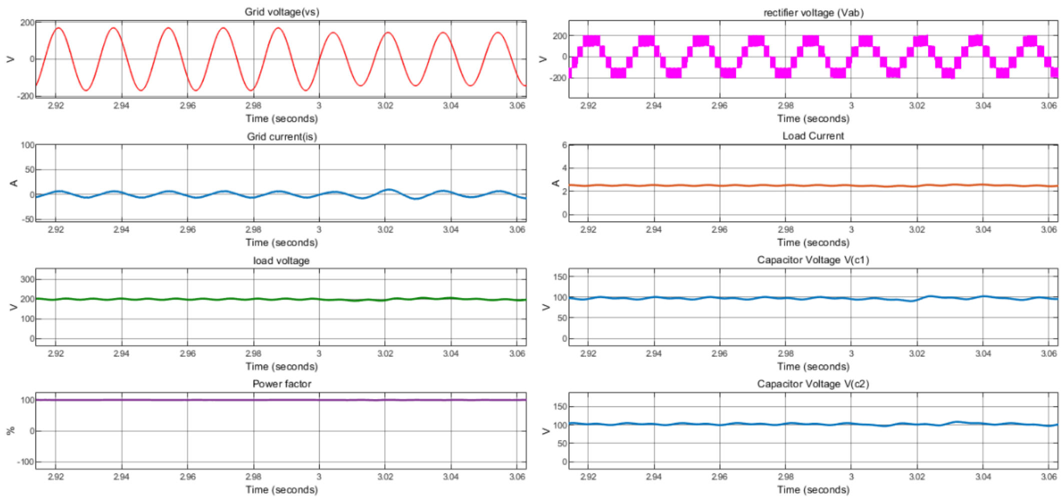

Fig.11: Simulation results during AC source voltage variation with the proposed method.

As seen in fig.12, the transient state response is substantially important. Hence, the transient state response of the rectifier system is compared with the smart controller designed in this paper and the PID controller in [1]. Fig.13 also presents the analysis results.

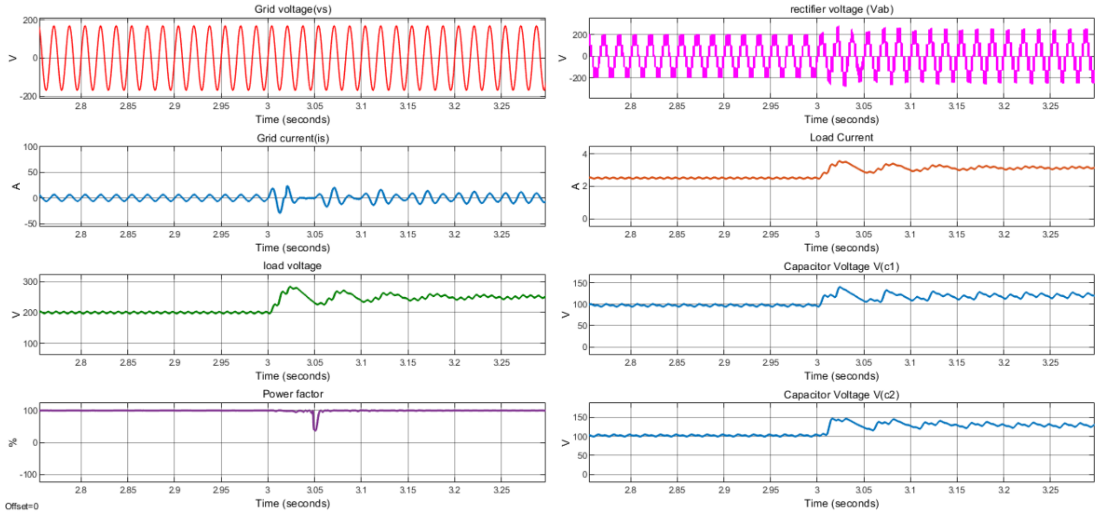

Fig.12: Simulation results during the increase in the DC voltage reference from 200V to 250V with the proposed method.

In Fig.13, the transient state response of the rectifier output for the smart controller and the PID controller is indicated. The black curve shows the direct output voltage waveform of the rectifier for the smart controller and the red curve represents the rectifier output waveform for the PID controller. As seen, the overshoot in the smart controller is somewhat better than the PID controller. This is a turning point for expressing the idea that the smart controller can be an alternative to the PID controller.

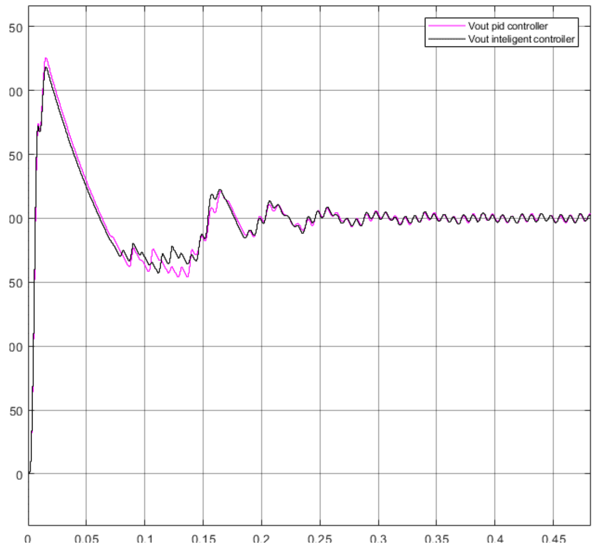

Fig.13: The transient state response of the smart controller and PID.

The Total Harmonic Distortion (THD) is one of the important rectifier parameters. The FFT analysis in MATLAB is used to obtain the THD of the rectifier input. In Fig.14, the FFT analysis of the rectifier is obtained for the smart controller. In this analysis, the calculated THD equals 36.91% within the 1000Hz frequency range.

In Fig.15, the FFT analysis of the rectifier is carried out for the PID controller. The THD value in this state is 37.07%. Considering the results of the FFT analysis, THD increases by approximately 1% when the smart controller is used.

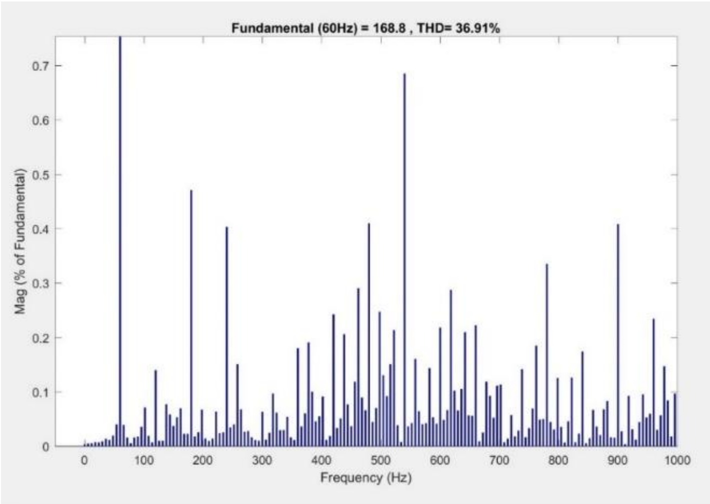

Fig.14: the curve for the FFT analysis of the smart controller.

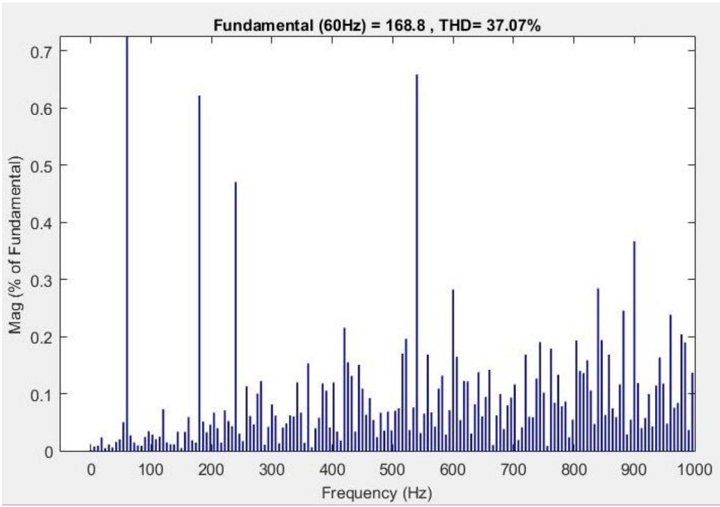

Fig.15: the curve for the FFT analysis of the PID controller.

5. Conclusion

In this paper, a smart controller was used instead of a PID controller and it was indicated that the smart controller, which was trained using the backpropagation algorithm, provided a response relatively faster and offered a relatively smaller maximum overshoot in the system output. THD in the system input was improved by 1%. The controller was first trained for a certain input, output, and load. Afterward, the input, load, and output were set to the desired values to obtain a correct response from the system. We managed to show that it is possible to use the smart controller in a five-level rectifier.

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