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Eliminating Harmonics and Voltage Ripples Using Optimal Constructive Recurrent Neural Network on Boost Rectifiers with Unbalanced Grid Sources

Angga Budi Setiawan*
Department of Electrical Engineering,
Universitas of Jember, Indonesia
anggabuset@gmail.com
Mohamad Agung Prawira Negara
Department of Electrical Engineering,
Universitas of Jember, Indonesia
magungpn@unej.ac.id
Bambang Sujanarko
Department of Electrical Engineering,
Universitas of Jember, Indonesia
sujanarko.teknik@unej.ac.id

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Abstract: Various new methodologies and techniques have been proposed to improve power quality. One of the parameters that affect power quality is harmonics. Voltage and current unbalance is a frequent problem. Electronic devices such as rectifiers and power distribution networks are negatively affected by this imbalance. The current in the grid will be severely distorted. The DC bus voltage will fluctuate or ripple frequently, perhaps twice as often as the frequency. Direct power control (DPC) and voltage-oriented control (VOC) are two examples of control strategies developed for rectifiers. In classical VOC, the voltage and current in the synchronous frame of reference (dq) are controlled using a proportional-integral (PI) controller. However, the PI controller in controlling the VOC current has the disadvantage that when one variable changes, the other variables will also change. PI cannot control itself independently. it is difficult to achieve an accurate linear mathematical model of the system required for PI controllers. In addition, PI controllers often struggle to work satisfactorily on parameter variations, nonlinearities, and load disturbances. in transient conditions, the Optimal Constructive Recurrent Neural Network(OCRNN) controller takes faster time to reach a stable state. when there is a change in the reference dc voltage, PI has a higher overshot voltage and a lower voltage drop than OCRNN and takes longer than the OCRNN controller.
Keywords: Harmonics, Rectifier, Neural Network

I. INTRODUCTION

Power quality refers to the consistency and reliability of electrical power, ensuring it meets the standards required for safe and efficient operation of electrical equipment and systems. It encompasses factors such as voltage stability, frequency variation, harmonics, and interruptions. To improve power quality, various new methodologies and techniques have been proposed, with harmonics being one of the primary influencing factors. The advent of power electronics components such as thyristors, triacs, and power transistors has significantly impacted the industrial sector. These components are utilized in developing inverters that inject harmonic currents into the power grid and draw non-sinusoidal currents from the utility grid, consequently degrading power quality in both distribution and industrial systems [1]. Harmonics have become a major problem for utilities at the distribution level, as non-sinusoidal voltages and currents adversely affect the performance of various electrical equipment connected to the system [2]. Therefore, harmonic analysis is required in power systems to reduce harmonics and ensure power quality standards are met [3]. Unbalanced load conditions can occur in electrical systems for many reasons. Unbalanced phase loads cause negative sequence and zero sequence currents (in four-wire systems) to flow into the electrical system. The transmission network will experience voltage distortion in the form of phase voltage unbalance and phase shifts due to unbalanced loads. Unbalanced voltages can cause damage and even failure of equipment that consumes electricity [4].

A three-phase voltage source PWM converter can achieve a constant DC voltage and a sinusoidal network current under ideal network voltage conditions. However, under conditions of unbalanced network voltages, there are twice the network frequency oscillations at the DC voltage, and the network current becomes highly distorted [5]. The main problem in renewable energy generation and smart grid integration is the control of Grid Connected Converters (GCC). Several Pulse Width Modulation (PWM) methods have been developed to reduce harmonic content. Selective harmonic elimination solves the transcendental equations characterizing harmonics, allowing for the computation of appropriate switching angles to eliminate specific harmonics at the output [6]. Traditionally, this type of converter is controlled using a standard isolated d-q vector control approach. However, recent studies have highlighted the limitations of standard vector controllers. These limitations can lead to poor power quality, inefficient generation and transmission, and potential blackouts, all of which result in losses for utilities and consumers [7]. DPC and VOC are two examples of several control strategies that have been developed for rectifiers. However, these control strategies are not useful when the source is unbalanced. DPC has recently been extended to control unbalanced grid voltage rectifiers. Nonetheless, this method has the disadvantages of difficulty in designing the input filter and power calculation when switching errors occur, resulting in a non-constant switching frequency that demands high inductance.In contrast, VOC offers several advantages, including a low sampling frequency for better performance and a constant switching frequency that simplifies the design of the input filter. However, in a classic VOC, the voltage and current in the synchronous reference frame (dq) are controlled using a PI controller. This PI controller in controlling the current in VOC has the drawback that when one variable changes, the other variables will also change, as PI cannot independently control itself [8].Reccurent Neural Network (RNN) can be trained and utilized to control GCC. It implements a dynamic programming (DP) algorithm and is trained using backpropagation through time (BPTT). To expedite training, BPTT is combined with robust propagation (RPPROP). Consequently, RNN-based controllers exhibit significantly faster response times, reduced overshoot, and generally superior performance compared to vector controllers [9]. The feedback mechanism enables the network to dynamically train and process sequences, thereby enhancing prediction [10]. RNNs are extensively employed in speech recognition and natural language processing applications owing to their capability to handle temporal sequences. However, due to their fully connected nature, RNNs necessitate substantial memory access, resulting in elevated power consumption. This constitutes a weakness of RNNs [9]. To address the limitations of the optimal GCC controller in practical scenarios, a novel RNN controller with an enhanced input structure is proposed to approximate the ideal optimal controller [11]. In Harmonics Reduction for a Four-Leg Distribution Network-Connected Single-Phase Transformerless PV Inverter System Using the Diagonal Recurrent Neural Network, the research investigates how solar radiation affects a single-phase PV inverter system connected to a four-leg distribution system (FLDN). The method proposed intends to mitigate current harmonic distortion (THDi) in distribution systems caused by varying and fluctuating radiation levels through intelligent control. This intelligent controller employs a Constructive Diagonal Recurrent Neural Network (CDRNN) [12]. The Optimal Constructive Neural Network (OCNN) artificial intelligence technique is a modification of the Levenberg-Marquardt Neural Network (LMNN) technique. OCNN automatically constructs the LMNN to minimize the error value. With each training session, the network allows for an increase in the number of hidden layers and neurons within each layer. To achieve the network with the lowest error value, OCNN compares the error value of each training result with the lowest error value obtained from the best network in each training session. Furthermore, to alleviate the training load, the number of OCNN inputs is minimized [13]. This paper introduces a grid-connected boost rectifier system employing an OCRNN controller, which is a type of RNN with a network structure constructed using a constructive algorithm. RNNs, characterized by iterative processing of inputs, store past information by incorporating it into their architecture [14]. A constructive learning algorithm, utilized in this study, iteratively refines the network to achieve a satisfactory solution. Typically, these algorithms commence by creating a small network, often with just one neuron and one hidden layer. Consequently, in this research, a modified RNN controller was employed to construct an optimized OCRNN to eliminating harmonics and voltage ripples on boost rectifiers with unbalanced grid sources

II. METHOD

Boost rectifier controlled using OCRNN is a circuit consisting of distribution network, load, boost rectifier, and OCRNN controller.

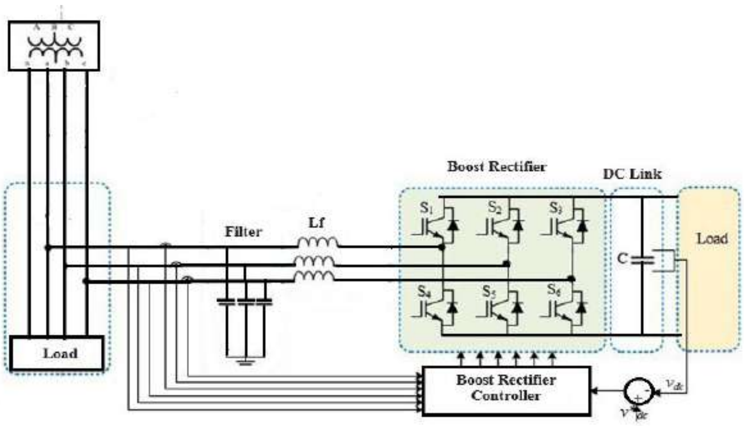

Fig 1. Rectifier boost control design using OCRNN

The rectifier is connected to an unbalance three-phase source. Fig 1 shows the design of OCRNN controller boost rectifier with unbalance grid.

2.1 Unbalance Grid

In three-phase systems, unbalanced loads can be caused by unequal load distribution of one phase. The changing power from each of the single-phase loads connected to the distribution system can cause imbalances in the power system. Due to unbalanced loads, physical systems with limited output and transmission impedances will experience phase shifts and voltage distortions in the form of phase voltage unbalances. Unbalanced voltages can result in malfunctions and even failure of power-consuming equipment [15]. The injection of harmonic and reactive to power system causes serious pollution[15]. Unbalanced loads can cause current and voltage imbalances in the generator or source. As a result, negative sequence current flows in the rotor winding. This circulating current increases internal losses and increases heat in the generator [7]. Then, harmonics will appear on the three phase source and the voltage ripple on the output of the rectifier. There are several methods to determine the degree of imbalance of a system, Percent Current Unbalance (PCU) and Percent Voltage Unbalance (PVU). There are several standards that can be used, one of which is ANSI / IEEE Std 241-1990.In this standard, voltage unbalance is defined according to Equation (1).To determine the degree of current unbalance, the same equation is used, but the voltage quantity is changed to current.

$$\mathrm{PVU} = 100\mathrm{x}\frac{\text{maximum deviation from the average phase voltage}}{\text{average phase voltage}} \ldots\ldots\ldots\ldots(1)$$

$$= 100\mathrm{x}\frac{\left|V_{average} - V_{a,b,c\ min}\ \text{atau}\ V_{a,b,c\ max}\right|}{\mathrm{Vaverage}}$$

In the situation of unbalanced network voltage and current, there will be a ripple in the rectifier voltage. This can be determined through the ripple ratio to determine the voltage ripple value. Ripple ratio (Rv) can be defined as the ratio of ripple amplitude Δ Vpp (peak-to-peak) to the average voltage Va, which is shown in equation 2.

$$R_v = \frac{\Delta V_{pp}}{V_a} \times 100\% \ldots\ldots\ldots\ldots(2)$$

2.2 There Phase Boost Rectifier

Fig. 2 depicts the boost rectifier design that is being studied. To link the rectifier to the network, a set of filters made up of resistances R and inductances L are used.

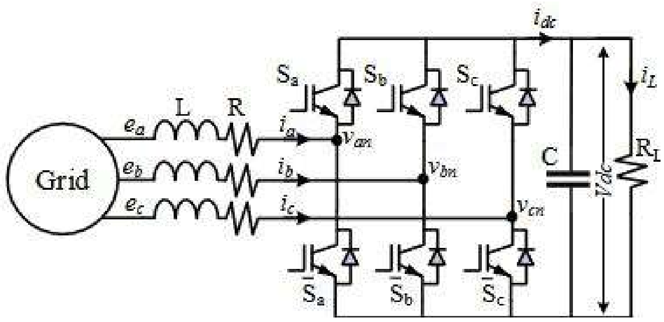

Fig. 2 Three phase boost rectifier circuit

The source voltages are ea, eb, and ec, while the input currents are ia, ib, and ic, in that order. The terminal voltages for each phase are van, vbn, and vcn, in that order. The load, the capacitance of the capacitor, and the dc-link voltages Vdc, C, and R are as follows [16, 17]. Based on Fig. 2, the average three-phase rectifier model can be described as shown in (3) in the abc coordinates.

$$L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} -R & 0 & 0 \\ 0 & -R & 0 \\ 0 & 0 & -R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a & v_{an} \\ e_b - & v_{bn} \\ e_c & v_{cn} \end{bmatrix} \ldots\ldots\ldots\ldots(3)$$

The DC capacitor voltage is :

$$C\frac{dV_{dc}}{dt} = \frac{1}{2}(\beta_a i_a + \beta_b i_b + \beta_c i_c) - \frac{V_{dc}}{R_L} \ldots\ldots\ldots\ldots(4)$$

Where

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{6}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} \beta_a \\ \beta_b \\ \beta_c \end{bmatrix}$$

The rectifier model in Equations (3) and (4) may be expressed in the synchronous dq frame Eq. (5) by using the Park transformation.

$$\begin{bmatrix} e_d \\ e_q \end{bmatrix} = L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} R & -\omega L \\ \omega L & R \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} V_{dn} \\ V_{qn} \end{bmatrix} \ldots\ldots\ldots\ldots(5)$$

Where ed, eq, id, and iq are the input voltages and input currents of the rectifier, respectively, while vdn and vqn are the terminal voltages of the rectifier. The dynamics of the DC output rectifier can be expressed through Eq. (6), where □d and □q are the modulation signals.

$$C\frac{dV_{dc}}{dt}+\frac{V_{dc}}{R_L}=\frac{3}{4}(\beta_d i_d + i_q i_q)\ldots\ldots(6)$$

Equations (7) and (8) are used to calculate the power value on the rectifier, including the reactive power Q and the active power P.

$$P=\frac{3}{2}(e_d i_d + e_q i_q)\ldots\ldots(7)$$
$$Q=\frac{3}{2}(e_d i_d - e_q i_q)\ldots\ldots(8)$$

Eqs. (7) and (8) become Eq. (9) by altering the d-axis vector of the network voltage (e.g. Ed = E and eq = 0).

$$P=\frac{3}{2}Ei_d;Q=\frac{3}{2}Ei_d\ldots\ldots(9)$$

2.3 VOC

For the purpose of controlling the boost rectifier, the DC output voltage, input voltage, and input current are equipped with sensors. The control system used is the VOC controller. Compared with the DPC method, the traditional VOC method in a synchronous rotating frame (dq0-frame) has been widely used due to its simple structure and ease of implementation [16]. The sync method plays an important role in the VOC method, as this method is used to extract the phase angle of the network voltage used in various Park and Park invers transformations and consequently provides the accuracy of current control in the frame dq0, for the PWM converter [15][17]. As shown in Fig 3.

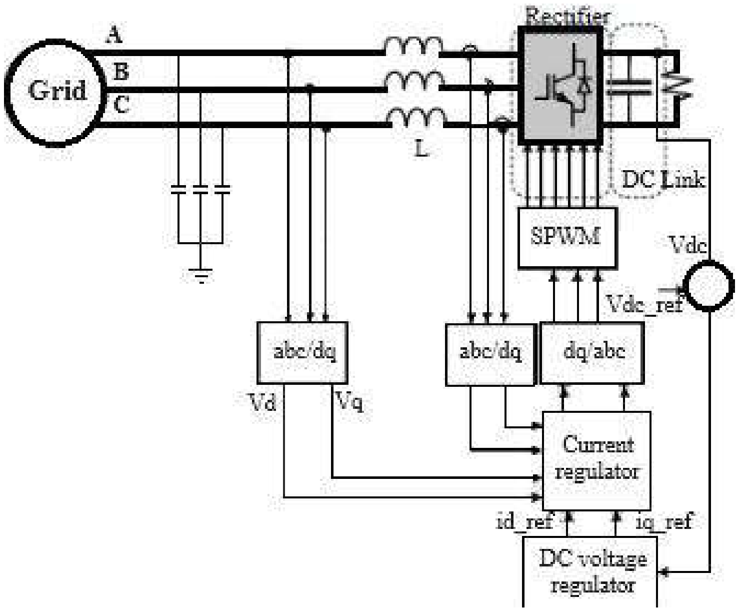

Fig. 3 VOC controller on rectifier

The control strategy used in this rectifier is VOC. The outline of the control technique is shown in Fig3. This controller consists of current and voltage controllers, as well as the abc/dq transformation and its inverse. There are 3 controller inputs, namely the input voltage and current signals and the output voltage of the boost rectifier. The boost rectifier source voltage and current signals are transformed from abc to dq. To change the abc to dq coordinates, the transformation shown in Equation (10) is used. If the variable v in Equation (10) is replaced with the variable i, then this equation applies to the current.

$$\begin{bmatrix}v_d\\v_q\end{bmatrix}=\frac{2}{3}\begin{bmatrix}sin(\omega t) & sin\left(\omega t-\frac{2\pi}{3}\right) & sin\left(\omega t+\frac{2\pi}{3}\right)\\ cos(\omega t) & cos\left(\omega t-\frac{2\pi}{3}\right) & cos\left(\omega t+\frac{2\pi}{3}\right)\end{bmatrix}\begin{bmatrix}v_a\\v_b\\v_c\end{bmatrix}\ldots(10)$$

The current controller output is a reference signal in the form of dq coordinates. To be used in PWM, it must first be converted into abc coordinates. To restore the voltage from dq coordinates to abc coordinates, Equation (11) is used.

$$\begin{bmatrix}v_a\\v_b\\v_c\end{bmatrix}=\begin{bmatrix}cos(\omega t) & -sin(\omega t) & 1\\ cos\left(\omega t-\frac{2\pi}{3}\right) & -sin\left(\omega t-\frac{2\pi}{3}\right) & 1\\ cos\left(\omega t+\frac{2\pi}{3}\right) & -sin\left(\omega t+\frac{2\pi}{3}\right) & 1\end{bmatrix}\begin{bmatrix}v_d\\v_q\\v_0\end{bmatrix}\ldots\ldots(11)$$

2.4 OCRNN

The OCNN Artificial intelligence technique is a modification of the LMNN technique. OCNN builds a Levenberg Marquardt network automatically to produce the smallest error value. Each training allows increasing the number of hidden layers and neurons within each layer. The OCNN network compares the error value of each training result with the lowest error value in the best network, which is done at each training session to get the network with the lowest error value.RNN is a type of artificial neural network architecture whose processing is called repeatedly to process its inputs. RNN stores information from the past by looping through it in its architecture, which automatically stores the information. A constructive learning algorithm is used to obtain a satisfactory solution for a number of iterations. This algorithm starts by creating a small network, usually one neuron and one hidden layer. OCRNN is an RNN that is trained using the OCNN network. The weight and bias update process is adjusted directly by utilizing negative gradient descent. Equation (12) illustrates the use of this algorithm from the Hessian (H) matrix approach. The algorithm's gradient calculation is expressed in Equation (13), where e(w) denotes the network error vector.

$$H(w) = J(w)^T J(w) \quad \ldots\ldots (12)$$
$$g(w) = J(w)^T e(w) \quad \ldots\ldots (13)$$

$J(w)$ = the Jacobian matrix containing the first derivative of the network error, shown in Equation .(14)

$$J(w) = \begin{bmatrix} \frac{\partial e_1(w)}{\partial w_1} & \frac{\partial e_1(w)}{\partial w_2} & \cdots & \frac{\partial e_1(w)}{\partial w_n} \\ \frac{\partial e_2(w)}{\partial w_1} & \frac{\partial e_2(w)}{\partial w_2} & \cdots & \frac{\partial e_2(w)}{\partial w_n} \\ \vdots & \vdots & & \vdots \\ \frac{\partial e_l(w)}{\partial w_1} & \frac{\partial e_l(w)}{\partial w_2} & \cdots & \frac{\partial e_l(w)}{\partial w_n} \end{bmatrix} \quad \ldots\ldots (14)$$

The Levenberg-Marquardt algorithm behaves like Newton's algorithm expressed by Equations (15) and (16).

$$\theta(k+1) = \theta(k) - \left[J_k^T J_k + \quad I\right]^{-1} J_k^T E_k \quad \ldots\ldots (15)$$
$$E_k = \sum_{l=1}^{N} (d_l - y_l)^2 \quad \ldots\ldots (16)$$

Where □ (k+1) is the new weight and bias as the gradient and the current weight function □(k)= {wji, bj } is calculated using Newton's algorithm.

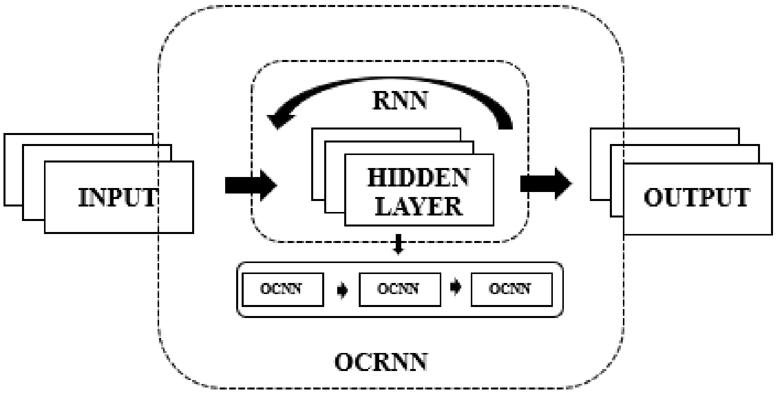

Fig. 4. OCRNN Structure

To test the rectifier controlled using OCRNN, the network load is made to fluctuate. the goal is to make the grid condition unbalanced. Distribution network conditions in an unbalanced state where each phase is given a different load and can change according to the following scenario:

1. During the initial condition, each phase is loaded with a resistive load of 150 kW on phase A, 75 kW on phase B and 100 kW on phase C.
2. When t = 0.05 s, a 50 kW resistive load is connected on phase A
3. when t = 0.10 s, a load of 75 kW is connected to phase B, while in phase C the load is 50 kW so that it becomes 50 kW

III. RESULT AND DISCUSSION

In the test process, the reverence voltage in the made varies. It's shown in the picture. The boost rectifier using the OCRNN control will be tested with under some conditions. The first condition is that the distribution network is in a balanced grid. For the second condition, that is, that it is in an unbalanced grid, each phase gives a different load and can vary according to the scenario. Fig. 5 shows variation of the Reference DC voltage

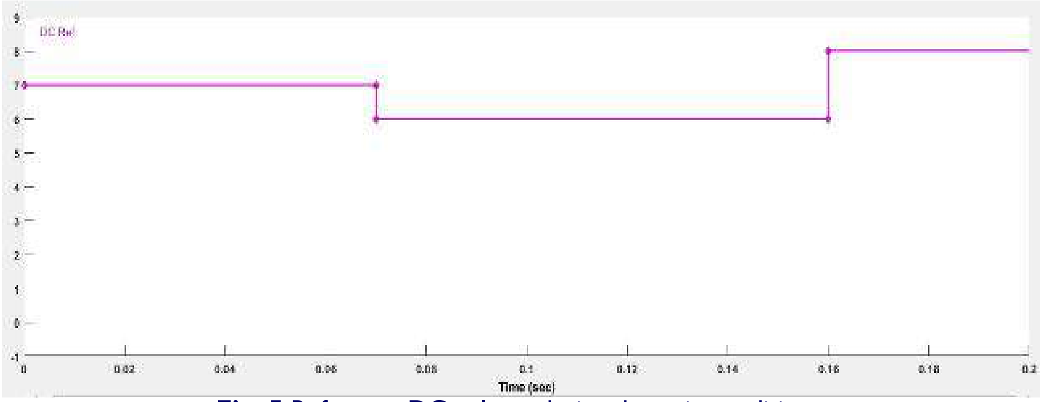

Fig. 5 Reference DC voltage during dynamic conditions

A. Balanced Grid Network

When the tissue is in a balanced state, each phase is given the same load of 50kVa. In this condition, two scenarios are tested. The first is when the reference voltage changes to 700 Volt again, falls to 600 Volt, and then rises back to 800 Volt. The third scenario is a change in the load on the boost rectifier. In the 0.18s the load of the boost rectifier decreases from 100 □ to 50 □.

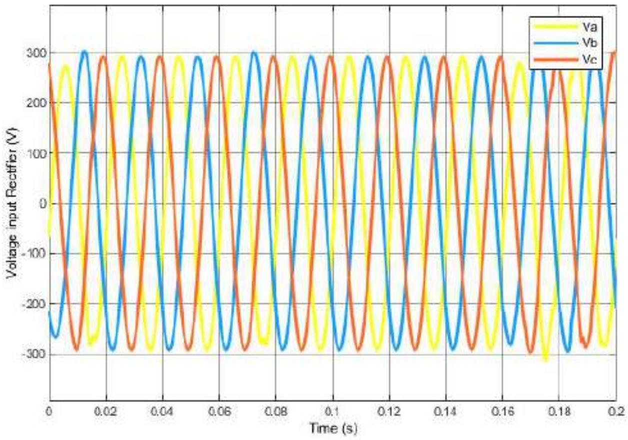

Fig.6 Voltage on Phases A B and C when network conditions are balanced controlled with PI

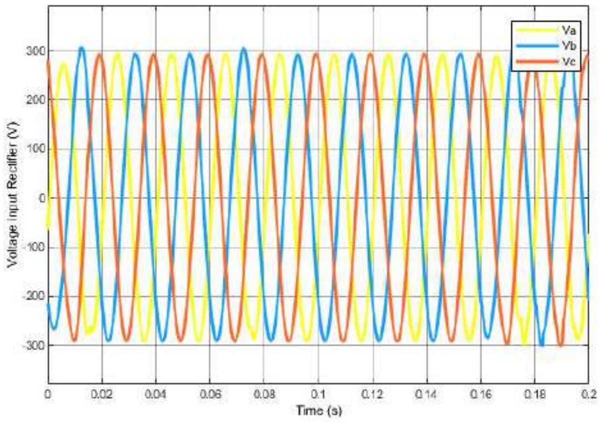

Fig.7 Voltage on Phases A B and C when network conditions are balanced controlled with OCRNN

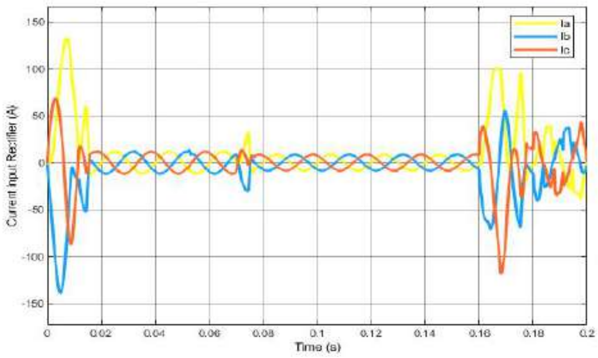

Fig.8 Current in Phases A B and C when network conditions are balanced controlled with PI

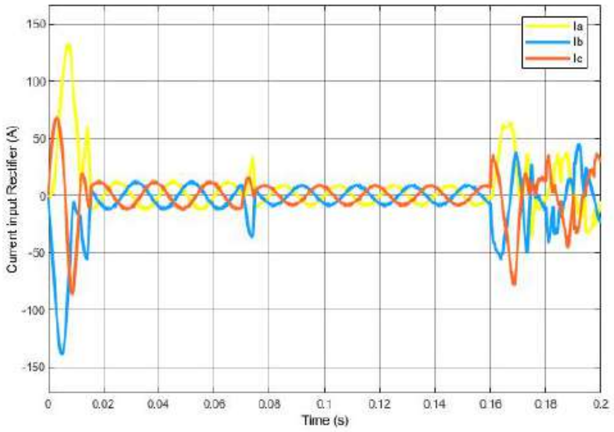

Fig.9 Current in Phases A B and C when network conditions are balanced controlled with OCRNN

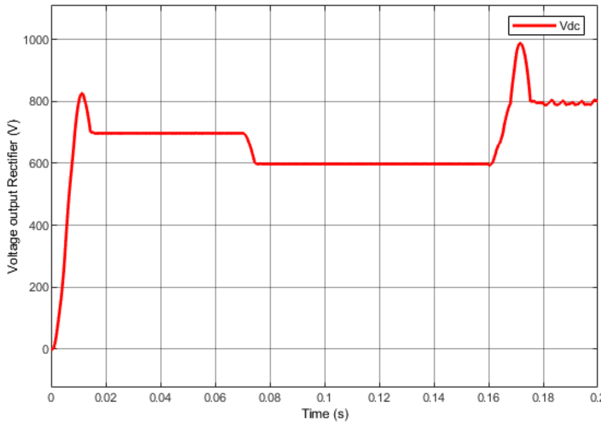

Fig.10 DC rectifier voltage in balanced network conditions controlled with PI

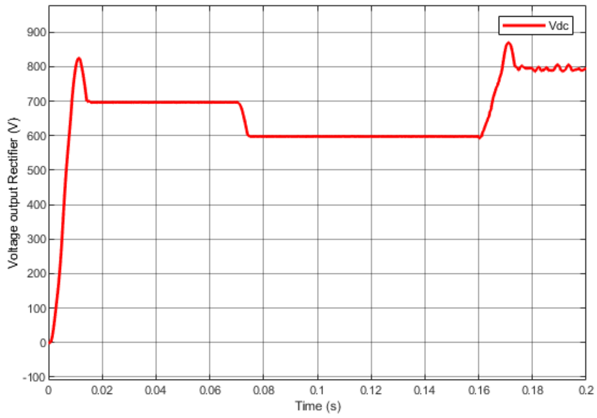

Fig.11 DC rectifier voltage in balanced network conditions controlled with OCRNN

After testing, the rectifier that is controlled using OCRNN and also PI can both reduce harmonic and voltage ripple. Fig 6 shows the input voltage response of a rectifier that is controlled using PI. Fig 7 shows the response of the input current of the rectifier in the control using PI, Fig 8 displays the response to the voltage of an input rectifier controlled with OCRNN, and Fig 9 shows the current response of an input rectifier which is in control using O CRNN. From the results of the image obtained from the simulation process, the two controllers are not very different in performing the harmony resulting from the two rectifiers. Fig 10 shows the output voltage of the boost rectifier that is controlled with PI while Fig 11 displays the outputs voltage from the boost rectifier controlled by OCRNN.

From the image of the simulation results, the two controllers have slight differences, i.e. when the load on the rectifier changes from the original 100 ☐ to 50 ☐ in the second to 0.18s. On the controller PI has a higher overshoot value than the controllers OCRNN. A three-phase rectifier in a balanced network takes advantage of the symmetry in the three-phase supply. It converts AC to DC with much less ripple. Connecting a rectifier to a balanced three-phase network significantly reduces the ripple in the DC output. connecting a rectifier to a balanced network, especially a three-phase network, results in lower ripple, reduced harmonics, higher efficiency, and better overall performance of the rectifier system. This makes such configurations highly desirable in industrial and high-power applications.

B. Unbalanced Grid

As previously stated, in this study on the grid unbalance conditions in the trial with the scenario of three things. The first when there is a change in the values of current and voltage, that is, at the second 0.1 to 0.13. The second change is the change of the reference voltage of the BR re 700 Volt, down to 600 Volts, then rise back to 800 Volt. The third scenario is the shift in the load on the boost rectifier. In the second-0.18s the load of the rectifier boost decreases from 100 □ to 50 □, or the load current is increased. It's done at a reference voltage of 800 volts.

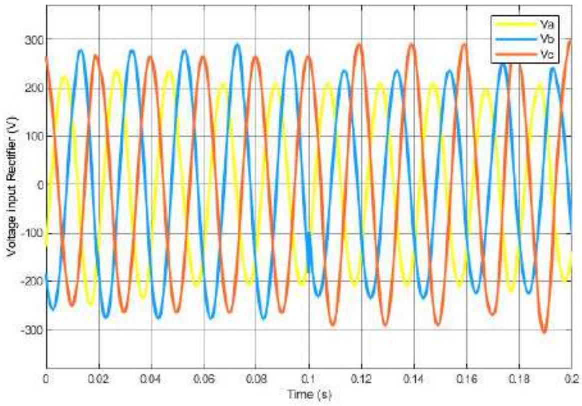

Fig. 12 The voltage in Phases A B and C in steady-state conditions under unbalanced conditions is controlled using PI

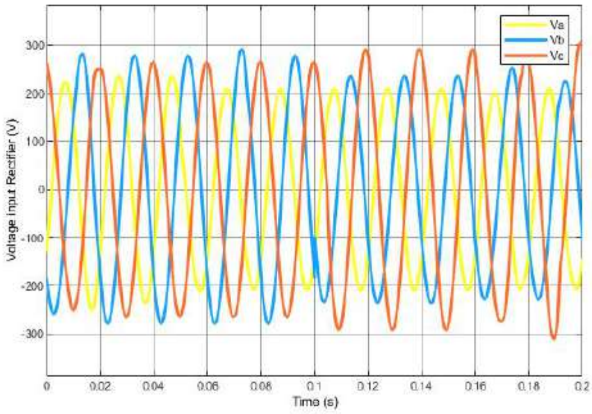

Fig. 13 The voltage in Phases A B and C in steady-state conditions under unbalanced conditions is controlled using NN

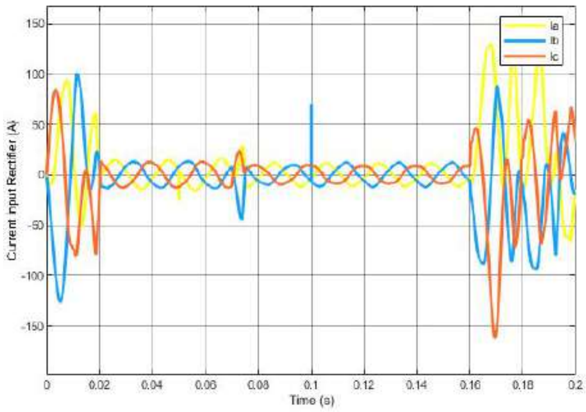

Fig. 14 The current in Phases A B and C in steady-state conditions under unbalanced conditions is controlled using PI

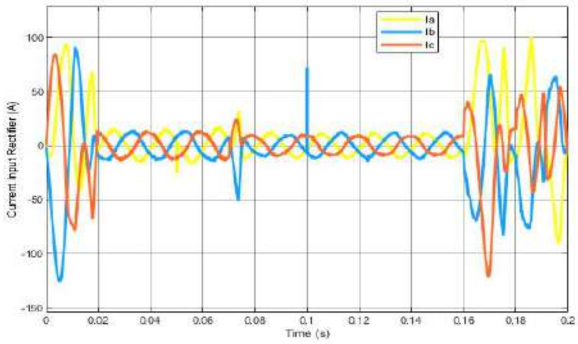

Fig. 15 The current in Phases A B and C in steady-state conditions under unbalanced conditions is controlled using NN

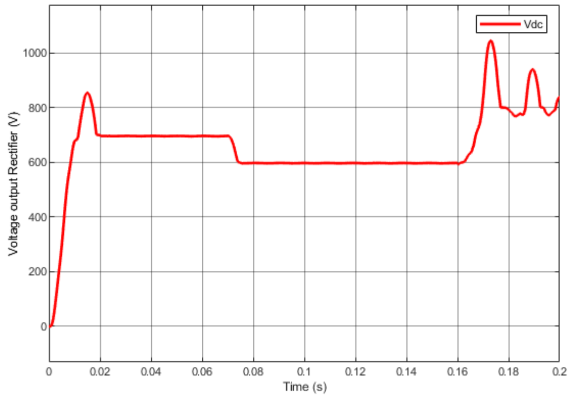

Fig. 16 The DC rectifier voltage in dynamic conditions under unbalanced conditions is controlled using PI

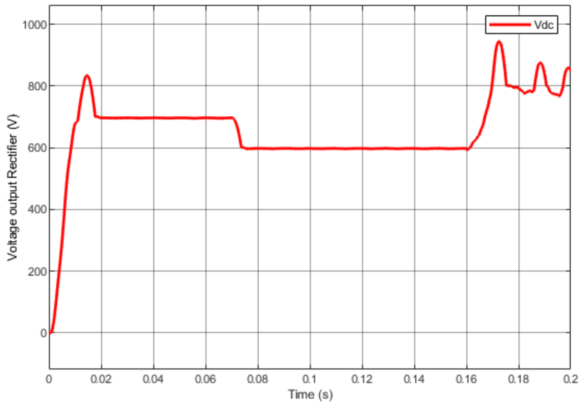

Fig. 17 The DC rectifier voltage in dynamic conditions under unbalanced conditions is controlled using OCRNN

The plots in figures above show the behaviour of the injected current and voltage with the above-mentioned scenario, resulting in the network voltage and network current profiles shown in fig 12untilfig 15respectively.The picture shows that the NN controller can reduce the presence of harmonics and voltage ripples when network conditions are unbalanced. It's just that it still has very small harmonics at certain times and voltage ripples at certain times. From the simulation results, fig 16 and fig 17 shows the boost rectifier controlled using OCRNN and the boost rectifier controlled using PI in reducing harmonics in an unbalanced distribution network show the same results. Of the two controllers, both can reduce harmonics with the same performance. This can be seen from the picture. While in eliminating voltage ripple, the two controllers show little difference. In transient conditions, namely when the new boost rectifier is turned on, the boost rectifier controlled using PI takes 18.75 ms to reach a stable state. While the boost rectifier controlled using OCRNN takes 17.31.

The PI controller has a voltage overshoot of 854 V, this shows 22% higher than the reference voltage of 700v. While OCRNN has a voltage over shoot of 834 V or 19% higher than the reference voltage. In the second condition, namely changes in the value of input current and voltage when an imbalance occurs in the distribution network at seconds 0.05s-0.1s. It appears in fig 10 and Figure 11 that the two controllers are not too affected by these changes. The third condition is when there is a change in the reference voltage. When the reference voltage changes from 700 to 600, the PI controller takes 5.3 ms while OCNN takes 3.6 ms to reach the reference voltage target. When the voltage changes from 600 to 800, the PI controller experiences a voltage drop first reaching 590 volts and then experiencing a voltage overshot of 1046 volts. While for OCRNN control, the voltage drops first by 590 volts then experiences a voltage overshot to reach 944 volts.

IV. CONCLUSIONS

Unbalanced distribution network conditions, do not affect the performance of the OCRNN controller and PI controller. both controllers are able to reduce voltage ripple on the output side of the boost rectifier. it's just that OCRNN is better than the PI controller. in transient conditions, the OCRNN controller takes faster time to reach a stable state. when there is a change in the reference dc voltage, PI has a higher overshot voltage and a lower voltage drop than OCRNN and takes longer than the OCRNN controller. based on the data above the OCRNN controller can complement the shortcomings of the PI controller.

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