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Design and Development of Rotating Magnetic Field inverter for Voltage Regulation

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Abstract*- In this paper, a novel idea of rotating magnetic field inverter is proposed which deals with the voltage fluctuation. The working principle of inverter is based on the field modulation technique that is changing flux in a coil induces an emf in that coil. The proposed inverter deals with power quality issues such as voltage sags and swells, harmonics, transients and voltage fluctuations in the distribution line. The inverter is composed of groups of coils arranged in a circular pattern and an output inductive coil is placed in the center. The rotating magnetic field in the outer groups of coils cuts the output central coil, an emf is induced in it due to varying field. The rotating magnetic field inverter work as a dynamic voltage restorer to compensate the voltage dips by injecting power into distribution lines and vice versa. The main contributions of proposed RMI are that it is a rotating magnetic field based novel inverter, produces continuous sine wave instead of staircase sine wave, provide phase synchronization and compensate voltage fluctuations. Comparing with the traditional DVRs, it consumes less power, highly efficient and have less circuit complexity. The whole model and architecture of RMI is being discussed. The validity of the proposed methodology is verified using MATLAB simulation.

***Index Terms*—**Field Modulation Theory, Inverter design, Inverter, voltage variations, Converter, Rotating Magnetic Field inverter

I. INTRODUCTION

WITH the evolution of new technologies and modern power electronic devices, the nature of electrical system is being transformed from conventional power system to modern and smart electrical system. Various renewable energy sources such as solar panels and wind turbines have been integrated into distribution networks [1]. Due to these RES and smart electrical system, the performance of the system has become a major concern. Power quality is an important issue in smart power system which can have impact on both customers and utilities. Power quality issues such as voltage and current harmonics, transients, and voltage dips and swells [2, 3] can harm the sensitive load devices. These issues need to be solved to provide the efficient and uninterrupted power to end users. This paper proposed an idea to improve the power quality issues and deal with voltage dips and swells. The voltage dips are the sudden drops in voltage up to 90 percent and 1 percent of the reference voltage for a short period of time [4]. Whereas the voltage swells are the sudden rise in voltage up to 10 percent or more of reference voltage value for short time interval [4, 5]. This section gives brief overview of previous methods and devices that were being used to deal with voltage fluctuations.

Normally in case of voltage fluctuations, the converters connected in series with distribution line induce positive or negative voltage into line [6, 7] to deal with voltage dips and swells. The flexible AC transmission systems (FACTS) devices are used for stability of voltage, power compensations and power quality improvements in the distribution networks [8]. These devices increase the efficiency of the transmission systems [9]. The FACTS controllers are normally used to allow the power to flow through the line under the normal conditions. In case of any faulty situation, it allows the line to transfer power close to its normal ratings [10].

To compensate the power quality issues, several devices like distribution static compensator (DSC), uninterrupted power supply (UPS) and dynamics voltage restorers (DVR) are used [11]. Among all of these, DVRs are most economical solution to deal with voltage dips and swells and commonly used in medium [12, 13] and small distribution systems. For continuous ac output voltage to sensitive load devices, DVR is used. The basic function of DVRs as mentioned by author in [14] is to find the voltage fluctuations occurred in any system. Then it feed the required voltage to bring back the voltage level to its normal working level. In [15, 16] author elaborate the working mechanism of DVRs as it injects voltage in series with the lines. It injects small amount of power in case of normal conditions. When disturbance occurs, DVRs estimates the amount of voltage required to protect the load through sinusoidal pulse width modulation (SPWM). The estimated amount of voltage then injected into the system to maintain the situation. In case of steady-state conditions, DVRs either absorb or transfer the active or reactive power to the system [29]. But when disturbance occurs, DVRs either absorb or deliver the active or reactive power to the dc-link.

The work reported in [18, 19] provides an overview of DVRs implementations in practice. The author in [17] gave a detailed studies of DVRs operations states. The follow of paper is based on the power circuit topologies and control method strategies. A brief review of different ac-ac converters-based DVRs are discussed in [20]. The benefit of using this converter is that it eliminates the need of dc storage batteries and thus size is reduced and become cost effective. Another buck boost inverter [21] is proposed which deals with voltage sags and swell of limited magnitude.

The commercially available multilevel inverter (MLI) topologies are discussed in [22]. These MLI are flying capacitor and H bridge type inverter. But the drawback is that in these types of inverters, the number of components increased when dealing with more voltage level. Another MLI [23] have uneven voltage distribution issue linked with dc link capacitor. Later on, various multilevel inverter topologies with comparatively less components discussed in the literature of [24]. These topologies are much efficient but these inverters require many isolated dc sources for voltage equalization of capacitors [28].

In this paper, a novel idea of rotating magnetic field inverter is proposed which deal with voltage regulations for DVR applications. The inverter gives rated output gain by using low voltage rated devices with less harmonic contents. The proposed model uses the distribution line voltage after ac to dc conversion which eliminates the needs of external dc sources. The inverter works on the principle of field modulation theory. The line voltage is measured continuously and compared with rated value to find the voltage variation in the line. The required voltage is then generated with the help of RMI and fed into the line to maintain the normal working voltage level. The main contributions are as follows; (I) rotating magnetic field based novel inverter (II) continuous sine wave instead of staircase sine wave (III) phase synchronization and (IV) voltage regulations. The previous mentioned inverters use a lot of electronic devices, capacitors, switches and line transformers which increases the circuit complexity. Multilevel inverters are not cost effective as they use a lot of components when working with more voltage levels. The model presented in this paper deals with more voltage levels using less circuit components which make it less complex. The need for a line frequency voltage injection transformer is eliminated in this model. Both voltage dips and swells are compensated with large magnitude coverage.

The flow of the paper is based on the brief theoretical background study in the section II. The section III describes the system description of RMI and section IV elaborate its detailed working methodology. Section V shows the MATLAB implementations and simulation result. The section VI tells about the conclusion and closing remarks.

II. THEORETICAL BACKGROUND OF MAGNETISM

The working principle of switching based inverter must take into account the phenomena of magnetism. The magnetism is one of the important aspects of electromagnetism [25]. The RMI model is based on Faraday's law of electromagnetism. According to law, the total emf induced in the coil of n turns and wound on core is due to rate of change of flux in that coil. It is represented as;

$$v(t) = n\frac{d\emptyset(t)}{dt} \qquad (1)$$

The flux generated due to change of current or voltage in the coil is the product of magnetic field density and area of the coil.

$$\emptyset = B.A_c \qquad (2)$$

So, the induced voltage in term of magnetic field density and area of coil is;

$$v(t) = nA_c\frac{dB(t)}{dt} \qquad (3)$$

The magnetic field generated in an element area can be represented by Ampere's law [26]. The law states that the sum of magnetic field across the circular groups of coils which is carrying a current is the product of proportionality constant and current in that coil;

$$\int B.dI = \mu_o I \qquad (4)$$

Where μo is the proportionality constant which is the permeability of free space. According to Ampere's law, the current in the coils is linked to magnetomotive force (MMF) and magnetic field H [27]. Magnetomotive force is related to property of material that give rise to magnetic field. Mathematically, it is represented as;

$$F = \emptyset R \qquad (5)$$

The mathematical equation of magnetomotive force is similar to ohm's law v = IR but the resistance is replaced by reluctance and it is written as;

$$R = \emptyset\frac{l}{\mu A_c} \qquad (6)$$

When two coils placed in a region where there is some air gap between them and they are linked with each other through mutual induction. The flux generated in one coil also linked with nearby coil and emf is induced in it which is represented as;

$$e_m = M\frac{dI}{dt} \qquad (7)$$

There are many factors that should be worth noticing while designing the magnetic circuit device that is (I). The core losses should be minimum so that saturation must not be occurred in the coils. (II) The distance between the two coils that are under the phenomena of mutual induction should be minimum to avoid the flux linkage factor. (III) The material of the core on which coil is wound should be such that there are minimum power losses. This theoretical information is put into practical use while designing a proposed RMI with the system description and working methodology in the next sections.

III. SYSTEM DESCRIPTION OF RMI

In this section, designing of RMI model based on Field Modulation Technique is discussed. The block diagram of RMI model is shown in Fig. 1. The voltage from distribution line is feedback into the RMI model through voltage and phase difference error, switching frequency generator and demultiplexer. Voltage difference error is used to detect any voltage change in distribution line and phase difference error is used to detect any phase change in the line voltage. In case of any voltage variation in the distribution line, the voltage is feedback to RMI through voltage difference error as it compares the line voltage with the rated voltage and produce output by taking the difference between line voltage and rated voltage and fed this difference value into switching frequency generator. The switching frequency generator produces the pulses of varying frequency according to difference voltage and fed it into demultiplexer. The outputs of demultiplexer are connected to eight group of coils through eight FET's.

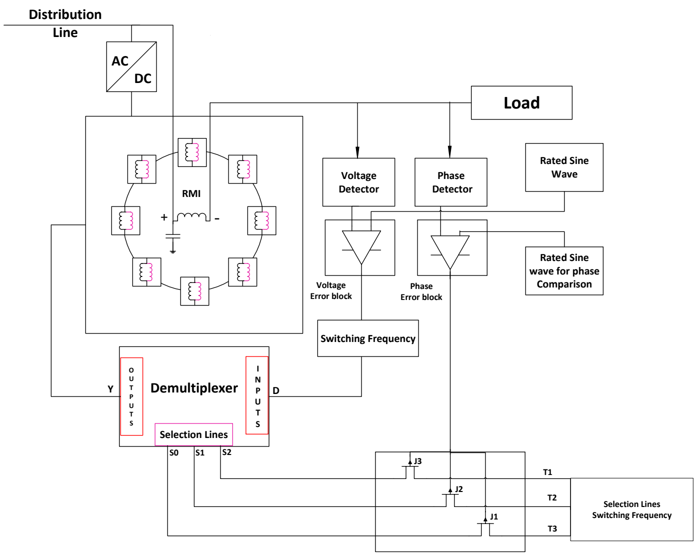

FIGURE 1. The block diagram of RMI based voltage regulation

The output of demultiplexer from y0 to y8 is decided on the basis of 3 selection lines that are connected to selection lines switching frequency generators i.e., T1, T2 and T3 through FETs J1, J2 and J3 as shown in Fig. 1. The frequency of selection line switching frequency generator is set in a manner that it forms eight possible combinations of selections lines through which eight outputs of demultiplexer can be operated sequentially during each cycle. The switching frequency generators are connected to selection lines only when the gate terminal of FETs are zero that is when the phase difference error gives zero output, this is possible only when the line voltage and rated sine wave are in phase. In case of any phase difference between the line voltage and reference sine wave the output of phase difference error will not zero but it shows some difference value. Now the FET's gate terminals have some contrast value, so the FET's don't work and selection lines don't receive any signal from switching frequency generators as a result demultiplexer don't produce any output to operate the RMI model. It means the model works only when the system has no phase difference between the line voltage and rated sine wave to avoid phase lag or lead. Now we will discuss how the RMI model works to deal with voltage variations.

The RMI model consists of eight groups of coils G1 to G8 that are arranged in a circular manner such that two coils are forming a group are in front of each other as shown in Fig. 2. There are two coils that are wound on same core such that L1 and L1', L2 and L2' so on, the following combinations shows that one coil is wound clockwise (i.e from L1 to L8) and other one is anticlockwise (i.e from L1' to L8'). The purpose of winding two coils on same core is to produce smooth circular magnetic field in the coils. The group of coils are energized sequentially as firstly G1 is energized which is consist of two coils L1 (which is wound on core in clockwise direction) and L5' (which is wound on core in anticlockwise direction), G2 is composed of L2 and L6' and so on up to G8. The theory behind forming groups having one coil of clockwise winding and other of anticlockwise winding is to keep the flow of current in one direction only. This groups of coil energized with the help of FETs as a result it will produce rotating magnetic field. The DC input took directly from the distribution line after AC to DC conversion as shown in Fig. 1.There is also an output inductive coil that is surrounded with groups of coils.

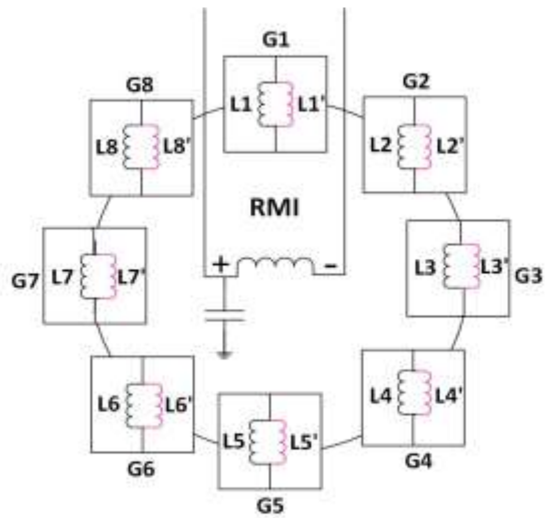

FIGURE 2. The block diagram of RMI model with eight group of coils

When the flux cuts centralized output inductive coil as a result an emf is induced in it. Consequently, the power is feed into the distribution line

IV. WORKING METHODOLOGY OF RMI

The schematic model of RMI is shown in Fig. 3 where all the groups of coils are shown along with FETs connected to the coils and demultiplexer attached with RMI. The sequence of operation of coils group in case of voltage fluctuations is being discussed with circuit model. There are two cases in which we use this circuit; one is to deal with voltage sag and second is to deal with voltage swell.

1. (Case−1) Voltage Dips:

The distribution line voltage is continuously compared with rated values with both comparators to check any voltage or phase variations. The phase error block allows switching frequency generator connection to demux only when there is no phase difference between line voltage and rated value. In case of in-phase line voltage signal, when the line voltage is compared with rated value using the voltage error block, then the output will be negative in case of voltage dips in distribution line. The negative output is then fed into the switching frequency generator which produce pulsating signal. The frequency of pulsating signal depends upon difference value. The pulsating data input is then given to the group of coils through demultiplexer. The output of demultiplexer is linked to coils through FETs i.e from K1 to K8.

The FETs receive the signal of demultiplexer at its gate terminal and provide dc voltage to coils through its drain terminal. For how long the pulsating data appears at respective group of coil depends upon the selection lines of demultiplexer.

The whole cycle is divided into eight equal parts through eight combinations of selection lines of demultiplexer and follow the sequence shown in Table 1;

TABLE 1. Switching table to show the flow of signal in each group of coils.

Demultiplexer inputs					**Demultiplexer outputs**							
En	**D**	**S2**	**S1**	**S0**	**Y0**	**Y1**	**Y2**	**Y3**	**Y4**	**Y5**	**Y6**	**Y7**
0	X	X	X	X	0	0	0	0	0	0	0	0
1	X	0	0	0	D	0	0	0	0	0	0	0
1	X	0	0	1	0	D	0	0	0	0	0	0
1	X	0	1	0	0	0	D	0	0	0	0	0
1	X	0	1	1	0	0	0	D	0	0	0	0
1	X	1	0	0	0	0	0	0	D	0	0	0
1	X	1	0	1	0	0	0	0	0	D	0	0
1	X	1	1	0	0	0	0	0	0	0	D	0
1	X	1	1	1	0	0	0	0	0	0	0	D

Now we see how RMI works to compensate the voltage dips.

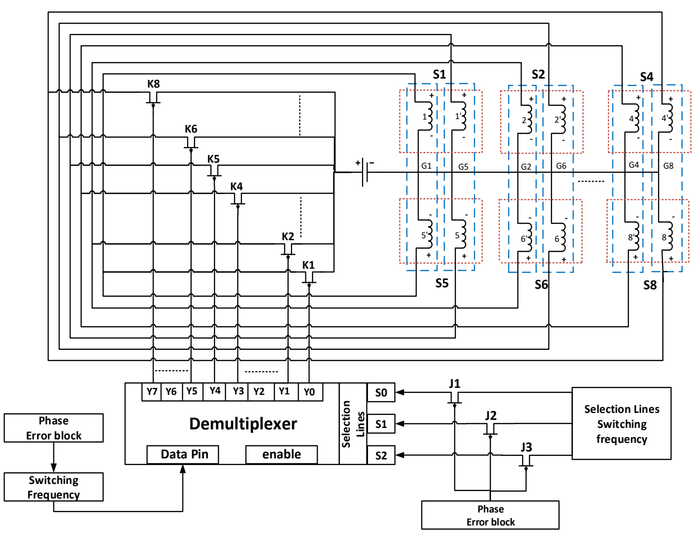

FIGURE 3. Circuit model of RMI architecture showing group of coils with controller and de-multiplexer.

A. During the interval (0-T/8):

Whenever the data input X appears at output terminal y0 than the switch K1 gate terminal that is connected with the output y0 of demultiplexer will receive a signal and the current will start flow through G1 group of coils i.e. L1 (clockwise winding) and L5' (anticlockwise winding). The path of the current is shown in Figure. 5. As the data input signal is pulsating having a specific frequency depending upon the output of controller 1, so group G1 also receive varying DC signal. The pulsating DC save the inductive coil from heating up as well as produces continuously varying magnetic field which cut the output inductive coil placed in the center as shown in Fig. 4.

B. During the interval (T/8-T/4):

Whenever the data input X appears at output terminal y1 than the switch K2 gate terminal that is connected with the output y1 of demultiplexer will receive a signal and the current will start flow through G2 group of coils i.e., L2 (clockwise winding) and L6' (anticlockwise winding). The path of the current is shown in Fig. 5. Similarly, the group of coils will be energized one by one in each cycle and it will produce a rotating magnetic field in the circuit. This rotating magnetic field will continuously cut the central output inductive coil. The purpose of capacitor as shown in Fig. 2 that is connected to the output coil is to filter the high frequency components in the induced voltage. How the flow of input and output produced in the circuit is depicted from the switching table shown in Table 1.

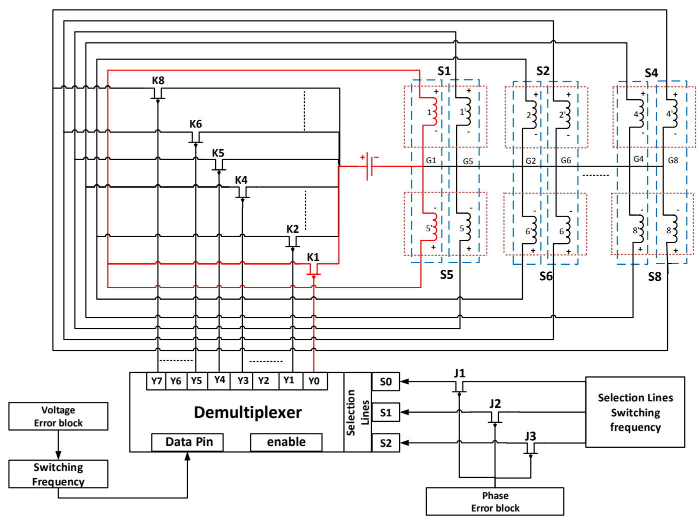

FIGURE 4. Circuit model of RMI architecture-Red path shows the flow of current during the interval of (0-T/8) in case of voltage dips.

2. (Case–2) Voltage Swells:

In case of in-phase line voltage signal, when the line voltage is compared with rated value using the voltage error block, then the output will be positive in case of voltage swell in distribution line. The output is then fed into the switching frequency generator which produce pulsating signal. The pulsating data input is then given to the group of coils through demultiplexer. The groups of coils are energized in a similar manner as that in case of voltage dips and follow the sequence shown in Table. 1.

A. During the interval (0-T/8):

Whenever the data input X appears at output terminal y0 than the switch K1 gate terminal that is connected with the output y0 of demultiplexer will receive a signal and the current will start flow through G1 group of coils i.e L1 (clockwise winding) and L5' (anticlockwise winding). The path of the current is shown in Fig. 4.

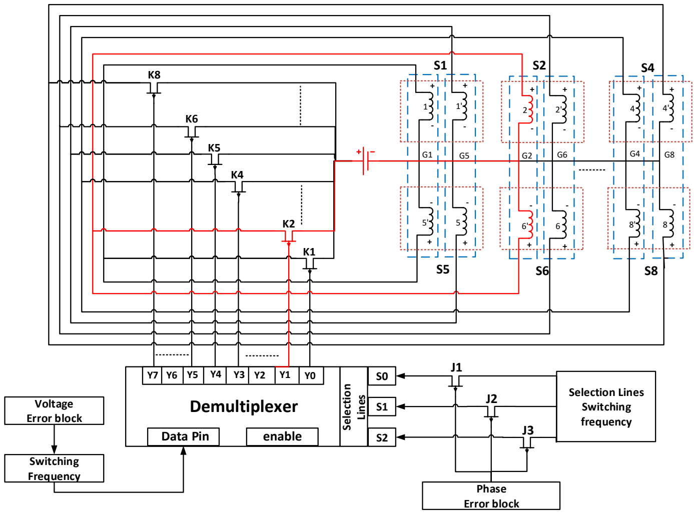

FIGURE 5. Circuit model of RMI architecture-Red path shows the flow of current during the interval of (T/8-T/4) in case of voltage dips.

B. During the interval (T/8-T/4):

Whenever the data input X appears at output terminal y1 than the switch K2 gate terminal that is connected with the output y1 of demultiplexer will receive a signal and the current will start flow through G2 group of coils i.e L2 (clockwise winding) and L6' (anticlockwise winding). The path of the current is shown in Fig. 5.

Similarly, as in case of voltage dips, the group of coils will be energized one by one in each cycle and it will produce a rotating magnetic field in the circuit. This rotating magnetic field will continuously cut the central output inductive coil. The changing flux in output coil produces the emf of specific value. The difference in this case is that whenever the power is injected into distribution line, it will be done in the same way as in voltage dips but with the reverse order as shown in Fig. 6. The connection of output inductive coil is switched to provide negative voltage to the distribution lines that will compensate voltage swells.

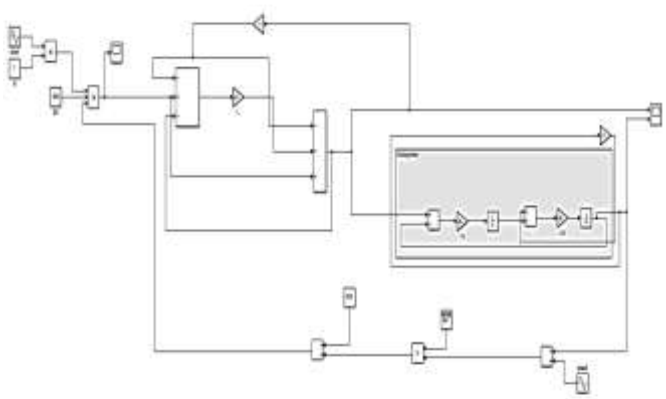

Figure 6. The block diagram of RMI based voltage regulation in case of voltage swells.

V. MATLAB MODEL AND SIMULATIONS RESULT

This section elaborates the MATLAB model of RMI and its simulations results.

A. MATLAB model of RMI:

The RMI is implemented using MATLAB Simulink. The model is shown in Fig. 7 where RMI mathematical model is displayed. The input is generated through switching frequency generator and fed into mathematical model of RMI and output is produced which is observed through the scope. The generated output is a high frequency signal which is passes through the filter circuit to eliminate the high frequency components and desired output result can be monitored through the scope.

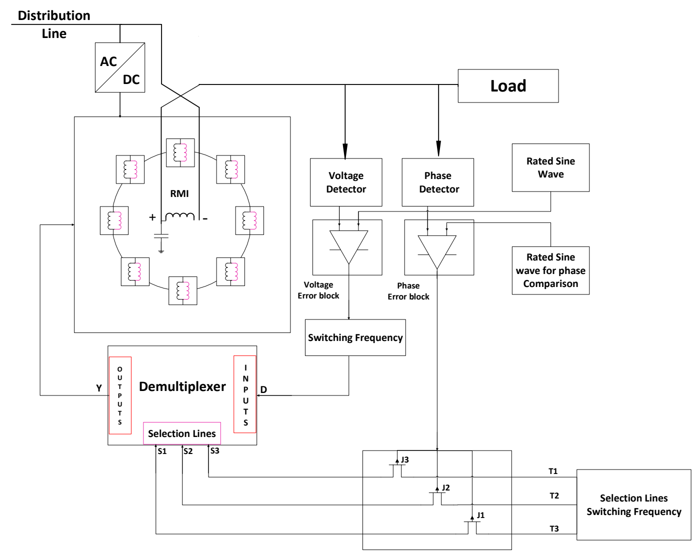

FIGURE 7. Simulink Model of RMI

B. Simulation Results:

The scheme for rotating magnetic field inverter is tested through MATLAB simulation. The output induced is smooth and without harmonics. The scope results for this model are shown in Fig. 8. Where there are two parts of scope display; one is voltage induced in the central output inductive coil and second is the filtered output which is a voltage that is being injected into distribution line to handle the voltage variation.

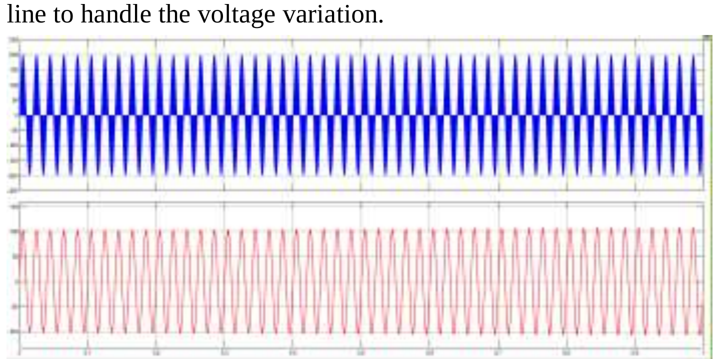

FIGURE 8. The simulation results (a) Voltage induces in the central output inductive coil (b)Filtered output which is a voltage that is being injected into the distribution line.

VI. CONCLUSION

This paper has proposed a novel idea of rotating magnetic field inverter which is based on field modulation theory to deal with voltage variation. The proposed inverter is easy to implement, has less complexity and relatively cheap as compared to previous mention inverters. The voltage is produced in output coil through rotation of magnetic field in a circular group of coils. The idea eliminate the use of external DC source and extra maintenance issue. In short, this novel RMI is more and more efficient economical which can deal with voltage sags and swells in a distribution line.

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