POWER REGULATION BY COUPLE HALF WAVE LPWM RECTIFIER AT THREE-PHASE LOADS

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Abstract: The paper presents an application of power control by couple half wave LPWM rectifiers processing at the energy distribution line. The switching method with the components of semiconductor for alternating energy control in the energy distribution line is used on alternating energy sources. In three-phase power line and load, power control and regulation are done with the proposed modulation correction index (MCI). Therefore, the simulation model of 3-phase energy distribution is established after the relationships between the energy sources and the circuit elements are determined by the circuit analysis method. The controls of the current and the voltage are done by trying at the different loads in the line at the simulation. According to the modulation correction index (MCI), currents of unbalanced loads are balanced by the proposed method on the power line. Then, the balance currents and powers that MCI provides are calculated. Finally, a power line of 15 km at length that is created by connecting the model of RLC is tested. Obtained results show the effectiveness of the proposed method.

Keywords: balance currents; circuit analysis; modulation correction index; LPWM half rectifiers; simulation of power control

1 INTRODUCTION

As well as the production of energy, the distribution and use of existing energy is of great importance. Therefore, many studies have been conducted on energy production and distribution [1-3]. Direct current (DC) energy in power lines and different loads is controlled by converting it into changing energy with pulse width modulation (PWM) inverters [4-9]. Therefore, the DC power source is derived from either renewable energy sources or alternating current (AC) sources. The DC energy from the AC source is converted back into AC current to control the power line. The quality of the converted energy from the DC current decreases since the current and voltage contain a high amount of harmonic distortion [10-12]. Multi-level inverters are used to eliminate or reduce these unwanted effects. This increases the cost of the system and the complexity of the system while it makes it difficult to find the faults that can be on the device. In addition, for some loads on the line controlled by the multi-level inverter, the quality of the current can be drawn to the desired level while the voltage of the generated energy cannot be obtained at the desired level [13, 14]. Thus, the paper presents a model of power control by inverse half rectifier processing method that uses the modulation correction index at an energy distribution line. On the line, there are two AC-source half-wave PWM rectifiers for each phase control current and voltage. Two GTO and two IGBT switches created are used on these half-wave rectifiers. This provides a mixed switches structure at the PWM rectifiers while it is intended for demonstrating the availability of different accessible switch preferences when performing energy control on the line. In the proposed control method, the effective values of the alternating current and voltage of the load are controlled by PWM on the load with dividing as the pulse width. Therefore, the modulation index values of PWM control the effective values of the current and voltage on the load without disturbing the sinus structures. In this study, the structure of the proposed line model is described

with making the circuit analysis of the power line. After the design of the power line model, three-phase line operation is performed in MATLAB Simulink for different load cases in the application phase.

Then, obtained results of the simulation are verified in experimentation. The current and voltages of different loads without changing the sinus structure of current and voltage vary depending on the modulation index on the line. In the simulation conducted for unbalanced loads, the impedance of the third phase is half of the other phase impedances while the two phases are equal to each other. Imbalance current of the line with the low impedance value is balanced by regulating the modulation index value. These modulation index values are named as modulation correction index (*MCI*) for balancing the power and current values in the first time. The imbalances due to different load conditions in the line are solved with different Modulation Correction Index values. These values are given in tables. When the results are analyzed, the value of the voltage controlled on the load has lower distortion than that of the previous line studies with inverters [15, 16]. In addition, these results can be obtained in a less complicated and inexpensive way using the proposed model. In addition, according to the results, the power distribution line is simulated for efficient power distribution and control without losing a lot of time and money. Then, the results are validated in experimentation. By taking this model into consideration, applications can be performed in less time and with less error rate. As the missing and difficult sides of the power line in the simulation can be determined, the accidents and errors that may occur are reduced and the loss of life and property is eliminated at the experimentation. According to the results obtained, it is observed that energy distribution and control are done effectively.

2 DESIGN OF THE PROPOSED MODEL

At three-phase power lines, six alternating energy sources are as V_s, four of semiconductor switches are for every phase, one resistive load is for every phase, and parallel RL loads are connected in series to the resistive load for each phase. Four semiconductor switches used for each phase are 2-IGBT and 2-GTO at the applications. Linear Pulse Width Modulation method (LPWM) is used to control switches because LPWMs determine the operating time of the switches. The comparison of the triangular signals and the direct signal to generate LPWMs is as in Fig. 1b. Fig. 1a shows the power circuit. The power line seen in Fig. 1a consists of three balanced phases. The accounts to be made for a phase are valid for every phase at the line. The switches S3 and S4 provide a negative voltage of half-wave with the second Vs source on the load, while the switches S1 and S2 provide a positive voltage of half-wave with the first V_s source on the load. In this case, the sinus voltage and the sinus current are formed by dividing according to the duty ratio of the LPWM on the load as in Eq. (1). α is phase difference. ωt is electrical angle as radians.

$$V_s = U_m \cdot \sin(\omega t) \tag{1}$$

D is the duty rate at which the PWMs are used to provide alternating sources over the load.

The alternating voltage that occurs on the line by two sources can be expressed as in Eq. (2).

$$V_s = DU_m \cdot \sin(\omega t) \tag{2}$$

The Z5 consists of a series of inductive (L) and resistive (R) loads. The unit of R is expressed in ohm, the unit of L in Henry, and the unit of Z6 in ohm.

Z_6 can be expressed as in Eq. (3).

$$\frac{1}{Z_6} = \frac{1}{j\omega L} + \frac{1}{R} \tag{3}$$

The Z_A is impedance of the first phase in ohm. Z_A can be expressed as in Eq. (4).

$$Z_A = Z_6 + R_1 \tag{4}$$

The I_1 is current of the first phase in ampere. I_1 can be expressed as in Eq. (5).

$$I_1 = \frac{DU_m \cdot \sin(\omega t)}{Z_A} \tag{5}$$

The Z_B is impedance of the second phase in ohm, The Z_C is impedance of the third phase in ohm. In the case of a balanced line, for voltages that have difference as the alpha-degree of phase, the current of the second and third phases of the line is found as in Eq. (6) and in Eq. (7).

$$I_2 = \frac{DU_m \cdot \sin(\omega t + \alpha)}{Z_B} \tag{6}$$

$$I_3 = \frac{DU_m \cdot \sin(\omega t + 2\alpha)}{Z_C} \tag{7}$$

If the B phase impedance is equal to half of the other phases, the operating times of the PWMs can be adjusted by calculating the Modulation Correction Index (MCI) to compensate for the current of the three phases.

D_1 is modulation index for C phase; D_2 is modulation index for B phase (MCI) and is calculated as shown below.

$$\frac{D_1 U_m \cdot \sin(\omega t + 2\alpha)}{Z_C} = \frac{D_2 U_m \cdot \sin(\omega t + \alpha)}{Z_B} \tag{8}$$

$$\begin{cases} Z_C = 2Z_B \\ U_m \cdot \sin(\omega t + \alpha) = U_m \cdot \sin(\omega t + 2\alpha) \end{cases} \tag{9}$$

$$\frac{D_1 U_m \cdot \sin(\omega t + 2\alpha)}{Z_C} = \frac{D_2 U_m \cdot \sin(\omega t + \alpha)}{2Z_C} \tag{10}$$

$$2D_1 = D_2 \tag{11}$$

$$\begin{cases} MCI = D_1 - D_2 \\ MCI = D_1 - \dfrac{D_1}{2} \\ MCI = \dfrac{D_1}{2} \end{cases} \tag{12}$$

The modulation index of the unbalanced line according to the calculated *MCI* value should be increased as half the modulation index value of the C phase. The length of the power distribution line shall be determined as series resistance (R_L), inductance (L_L), capacitor (C_C) loads to be connected serially to the circuit in Fig. 1.

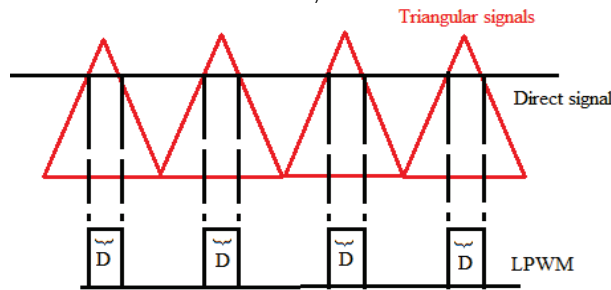The Z_W represents the line length impedance. Z_W is described as in Eq. (13).

$$Z_W = j\omega L_L + R_L + \frac{1}{j\omega C_C} \tag{13}$$

Impedance (Z_L) of the power distribution line can be found as in Eq. (14).

$$Z_L = Z_A + Z_W \tag{14}$$
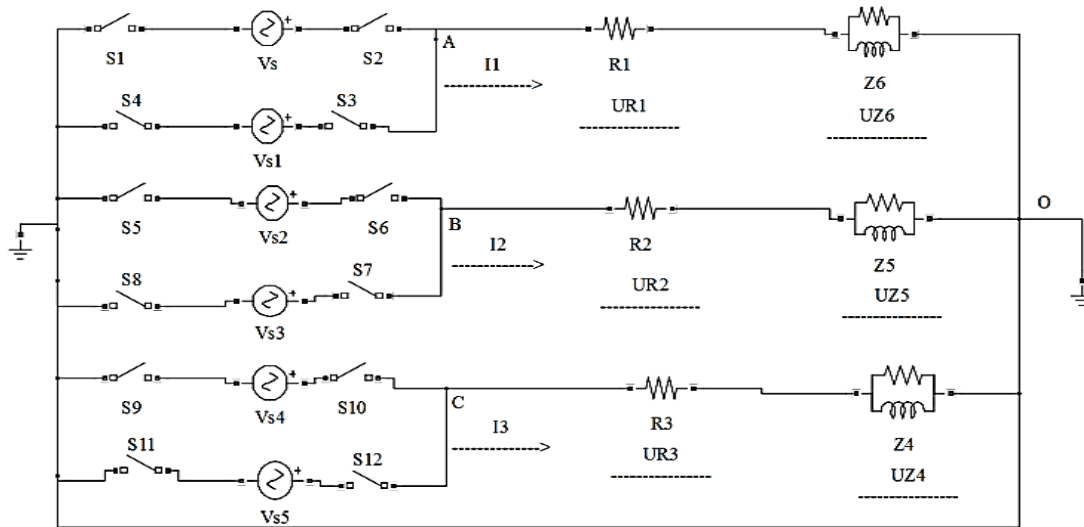
a)

b)

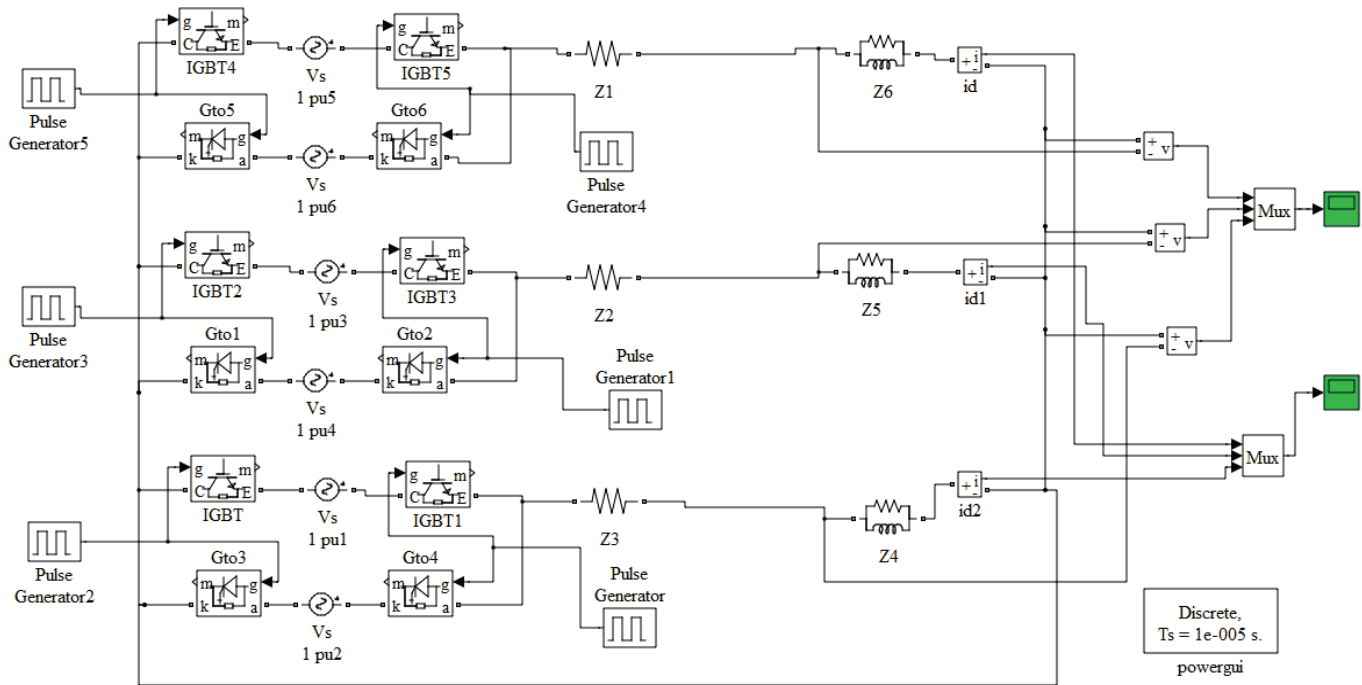**Figure 1** a) the power line of circuit model, b) LPWM

Figure 2 Balanced power line

3 POWER LINE APPLICATION

The impedances of each phase are equal to each other for the application in Fig. 2. Z1 = Z2 = Z3 = 10 ohm, Z6 = Z5 = Z4 = 10 + j0.1, V_s = 220 volt, Modulation index = 0.95, Switching frequency is 100 kHz.

The circuit in Fig. 2 provides a three-phase alternating voltage at 60 Hz of frequency to the power line. The voltage

and distortion value of voltage are given in Fig. 3, while the current is as in Fig. 4.

a)

Selected signal: 6 cycles. FFT window (in red): 2 cycles

Fundamental (60Hz) = 104.7 , THD= 4.59%

b)
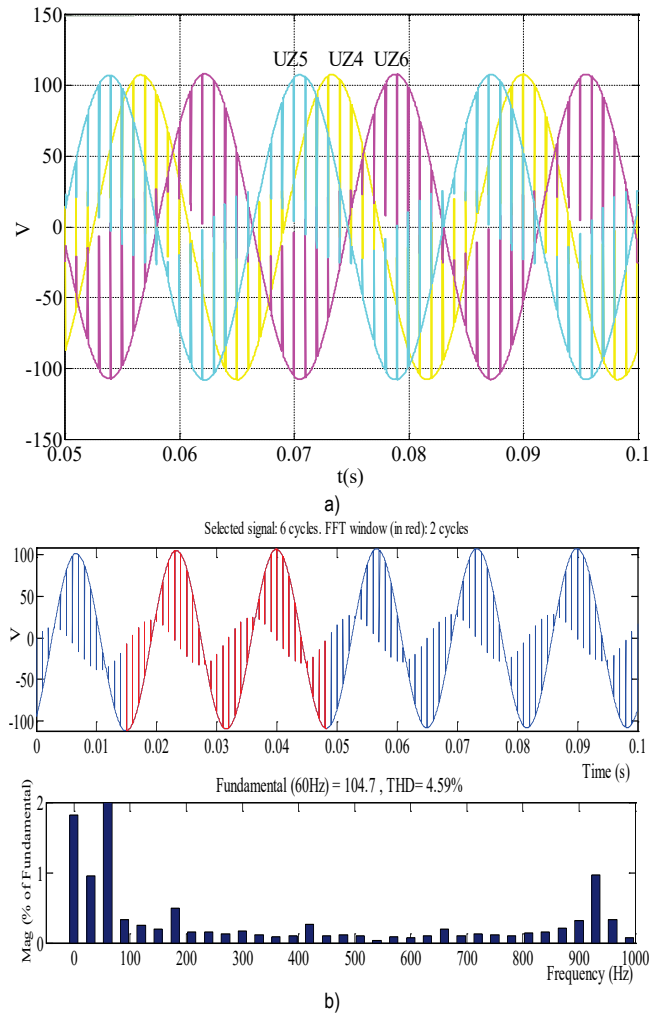
Figure 3 a) 3-phase alternating voltage at 60 Hz of frequency, b) distortion value of voltage
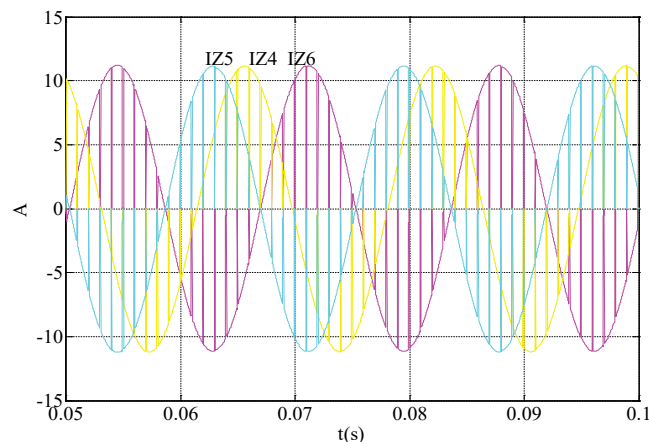
Figure 4 3-phase alternating current at 60 Hz of frequency for balanced load

For the balanced three-phase loads that are Z4, Z5, Z6 in Fig. 3a, a three-phase alternating voltage with 60 degree of the phase difference is provided on load. These voltages are formed on the load according to arranging the modulation

index value. In Fig. 3b, the THD value of the voltage on the load is 4.49%. 104.7V is created with 0.95 of modulation index on load. While the THD values of the voltage supplied to the load with PWM inverters can exceed 100%, a level of 4.59% can be achieved for the proposed method. In the simulation, the current obtained is given at the 0.8 of modulation index in Fig. 4.

For the balanced three-phase load that is ZA, ZB, ZC in Fig. 4, a three-phase alternating current with 60° of the phase difference is provided on load. 10.7 A is created with 0.95 of modulation index on load. If loads in Fig. 2 are changed as $Z1 = Z3 = 10$ ohm and $Z2 = 5$ ohm; Z5 and Z4 are $10 + j0.1$, $Z6 = 5 + j0.05$. D is 0.8. Then, three phases are unbalanced. Model is performed according to unbalanced loads; loads currents are shown in Fig. 5.
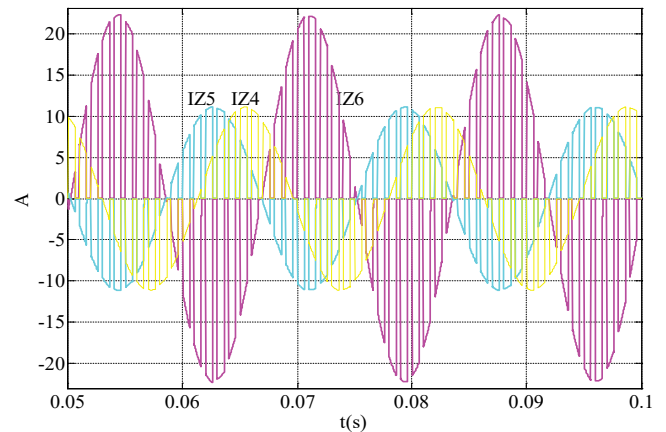

Figure 5 Unbalanced loads of currents

The load at less impedance value generates more current. Currents of IZ5 and IZ4 are 12 A at the maximum while Currents of IZ6 is 24A at the maximum. The difference in impedances of the loads is half. Therefore, the load with a low impedance of the modulation index must be twice the load with high impedance. Fig. 6 shows the balanced loads with the effective value of their current.
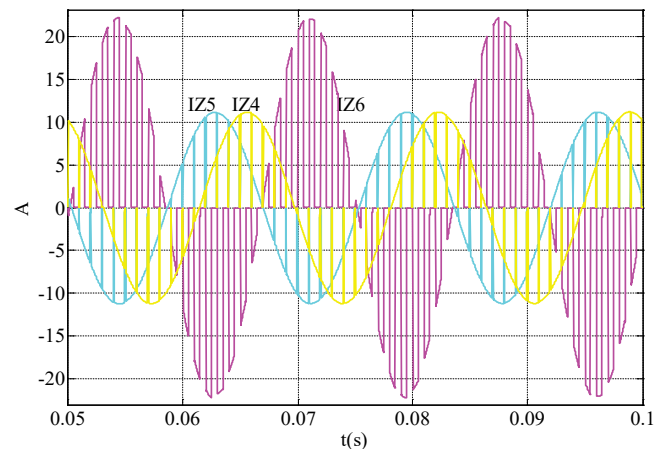

Figure 6 The balanced loads with the effective value of their current

MCI is 0.5 according to Eq. 11. Therefore, when the modulation index for IZ6 is made to 0.45, the modulation

index for IZ4 and IZ5 is 0.9. Then, IZ4 = IZ5 = IZ6 = 10.8A for effective value of the current [7].

When the three-phase line is supplied with 220 volts; balancing currents and MCIs are given in Tab. 1 for different line imbalances. When the three-phase line is supplied with 330 volts; balancing currents and MCIs are given in Tab. 2 for different line imbalances. Z is 10 ohms as impedances.

Table 1 Correction currents and MCIs of 3-phase lines fed with AC sources of 220V

D	ZA	ZB	ZC	MCI	$I_{max} - I_{ef}$ for I_{ZA} and I_{ZC}	$I_{max} - I_{ef}$ for I_{ZB}	I_{ef} f or I_{ZA} and I_{ZC} with MCI
0.8	Z	0.9Z	Z	0.89	22A-17.6A	24.4A-19.6A	19.6A
0.8	Z	0.8Z	Z	0.99	22A-17.6A	27.5-22A	22A
0.7	Z	0.9Z	Z	0.776	22A-15.4A	24.4A-17.08A	17.08A
0.7	Z	0.8Z	Z	0.875	22A-15.4A	27.5-19.25A	19.25A
0.7	Z	0.7Z	Z	0.99	22A-15.4A	31.42A-22A	22A
0.7	Z	0.6Z	Z	X	22A-15.4A	36.6A-25.66A	X
0.6	Z	0.9Z	Z	0.666	22A-13.2A	24.4A-14.66A	14.66A
0.6	Z	0.8Z	Z	0.756	22A-13.2A	27.5-16.65A	16.65A
0.6	Z	0.7Z	Z	0.857	22A-13.2A	31.42A-18.85A	18.85A
0.6	Z	0.6Z	Z	0.99	22A-13.2A	36.66A-22A	22A
0.6	Z	0.5Z	Z	X	22A-13.2A	44A-26.4A	X
0.6	Z	0.4Z	Z	X	22A-13.2A	55-33A	X

Table 2 Correction currents and MCIs of 3-phase lines fed with AC sources of 330V

D	ZA	ZB	ZC	MCI	$I_{max} - I_{ef}$ for I_{ZA} and I_{ZC}	$I_{max} - I_{ef}$ for I_{ZB}	I_{ef} f or I_{ZA} and I_{ZC} with MCI
0.8	Z	0.9Z	Z	0.89	33A-26.4A	36.6A-19.6A	29.4A
0.8	Z	0.8Z	Z	0.99	33A-26.4A	41.25A-33A	33A
0.7	Z	0.9Z	Z	0.776	33A-23.1A	36.6A-25.62A	25.62A
0.7	Z	0.8Z	Z	0.875	33A-23.1A	41.25A-28.87A	28.87A
0.7	Z	0.7Z	Z	0.99	33A-23.1A	47.3A-33A	33A
0.7	Z	0.6Z	Z	X	33A-23.1A	54.9A-38.49A	X
0.6	Z	0.9Z	Z	0.666	33A-19.8A	36.6A-21.99A	21.99A
0.6	Z	0.8Z	Z	0.756	33A-19.8A	41.62A-24.97A	24.97A
0.6	Z	0.7Z	Z	0.857	33A-19.8A	47.13A-28.27A	28.27A
0.6	Z	0.6Z	Z	0.99	33A-19.8A	54.99A-33A	33A
0.6	Z	0.5Z	Z	X	33A-19.8A	66A-39.6A	X
0.6	Z	0.4Z	Z	X	33A-19.8A	82.5A-44A	X

Table 3 Balancing currents and balancing powers for three-phase system with 220 volt input

Impedance (Ohm)	MI	MCI	Pb(VA)	I_b(A)
0.9Z	0.8	0.89	440	2
0.8Z	0.8	0.99	968	4.4
0.9Z	0.7	0.776	309	1.68
0.8Z	0.7	0.875	847	3.85
0.7Z	0.7	0.99	1452	6.6
0.6Z	0.7	X	X	X
0.9Z	0.6	0.666	321,2	1.46
0.8Z	0.6	0.756	759	3.45
0.7Z	0.6	0.857	1243	5.65
0.6Z	0.6	0.99	1936	8.8
0.5Z	0.6	X	X	X
0.4Z	0.6	X	X	X

In Tab. 1, the imbalances generated in the impedances ranging from 10 ohm to 4 ohm on the line are controlled by the modulation index that is from 0.8 to 0.6. While the effective value of the line current is balanced twice in the 0.8 modulation index, the effective value of the line current can be set at three times for the 0.7 of modulation index value. In the case of 0.6 modulation index, the effective value of the line current can be compensated four times. For the 0.9Z value of ZB at the 0.8 of the modulation index, the MCI value is 0.89. For the 0.8Z value of ZB at the 0.8 of the modulation index, the MCI value is 0.99. At the 0.7 of the modulation index, the MCI value is 0.776 for the 0.9Z value of ZB while the MCI value is 0.875 for the 0.8Z value of ZB. The line can be balanced in nine of twelve trials, while the line cannot be

balanced in three cases. Although a current of 25.6 A is required for the compensation of the line, the maximum current that the line can achieve is 22A at 0.99 of modulation index. Current imbalance of the 6 ohm of the impedance controlled by 0.7 modulation index cannot be compensated. Thus, MCI is shown with X. Although a current of 26.4 A is required for the compensation of the line, the maximum current that the line can achieve is 22A at 0.99 of modulation index. Current imbalance of the 5 ohm impedance controlled by 0.6 modulation index cannot be compensated. So, MCI is shown with X for it.

Although a current of 33 A is required for the compensation of the line, the maximum current that the line can achieve is 22 A at 0.99 of modulation index. Current imbalance of the 4 ohm impedance controlled by 0.6 modulation index cannot be compensated. Thus, MCI is shown with X for it. In Tab. 2, the imbalances generated in the impedances ranging from 10 ohm to 4 ohm are controlled on the line from 0.8 modulation index to 0.6 modulation index. The line can be balanced in nine of twelve trials, while the line cannot be balanced in three cases. Tab. 3 shows the balancing current and balancing power generated by arranging of the MCI to compensate for the three-phase power line, which has 220V of the input voltage source. Tab. 4 has the balancing current and balancing power generated by arranging of the MCI to compensate for the three-phase power line, which has 330V of the input voltage source. The balance current (I_b) is the difference between the high phase

current and the low phase current values. This value can be expressed as follows.

$$I_b = I_{ZA} - I_{ZB} \qquad (14)$$

$$I_b = I_{ZA} - I_{ZB} \qquad (15)$$

The balance power (P_b) can be found as in Eq. (16) while U_i is input voltage for the line.

$$P_b = U_i \cdot I_b \qquad (16)$$

For the impedance of 0.9Z at Tab. 2, a compensation power of 440 VA and a balancing current of 2 A are provided with a 0.89 *MCI* value when a compensation power of 968VA and a balancing current of 4.4 A are provided with a 0.99 of *MCI*. The first greatest balancing power and current are 1936 VA and 8A that are provided with 0.99 of *MCI* at the 0.6Z of impedance, while the second greatest balancing power and current are 1452 VA and 6.6 A that are provided with 0.99 of *MCI* at 0.7Z of the impedance. When the

impedance value (Z) is 10 ohm, the balancing current and power cannot be provided with 0.6 of modulation index to the system supplied with 220 volts for 0.5Z and 0.4Z impedance values. When the impedance value (Z) is 10 ohm, the balancing current and power cannot be provided with 0.7 of modulation index to the system supplied with 220 V for 0.6Z of the impedance values.

Table 4 Balancing currents and balancing powers for three-phase system with 330 volt input

Impedance (Ohm)	MI	MCI	P_b(VA)	I_b(A)
0.9Z	0.8	0.89	880	4
0.8Z	0.8	0.99	1936	8.8
0.9Z	0.7	0.776	618	336
0.8Z	0.7	0.875	847	7.7
0.7Z	0.7	0.99	2904	13.2
0.6Z	0.7	X	X	X
0.9Z	0.6	0.666	642	2.92
0.8Z	0.6	0.756	1518	6.9
0.7Z	0.6	0.857	2486	11.3
0.6Z	0.6	0.99	3872	17.6
0.5Z	0.6	X	X	X
0.4Z	0.6	X	X	X
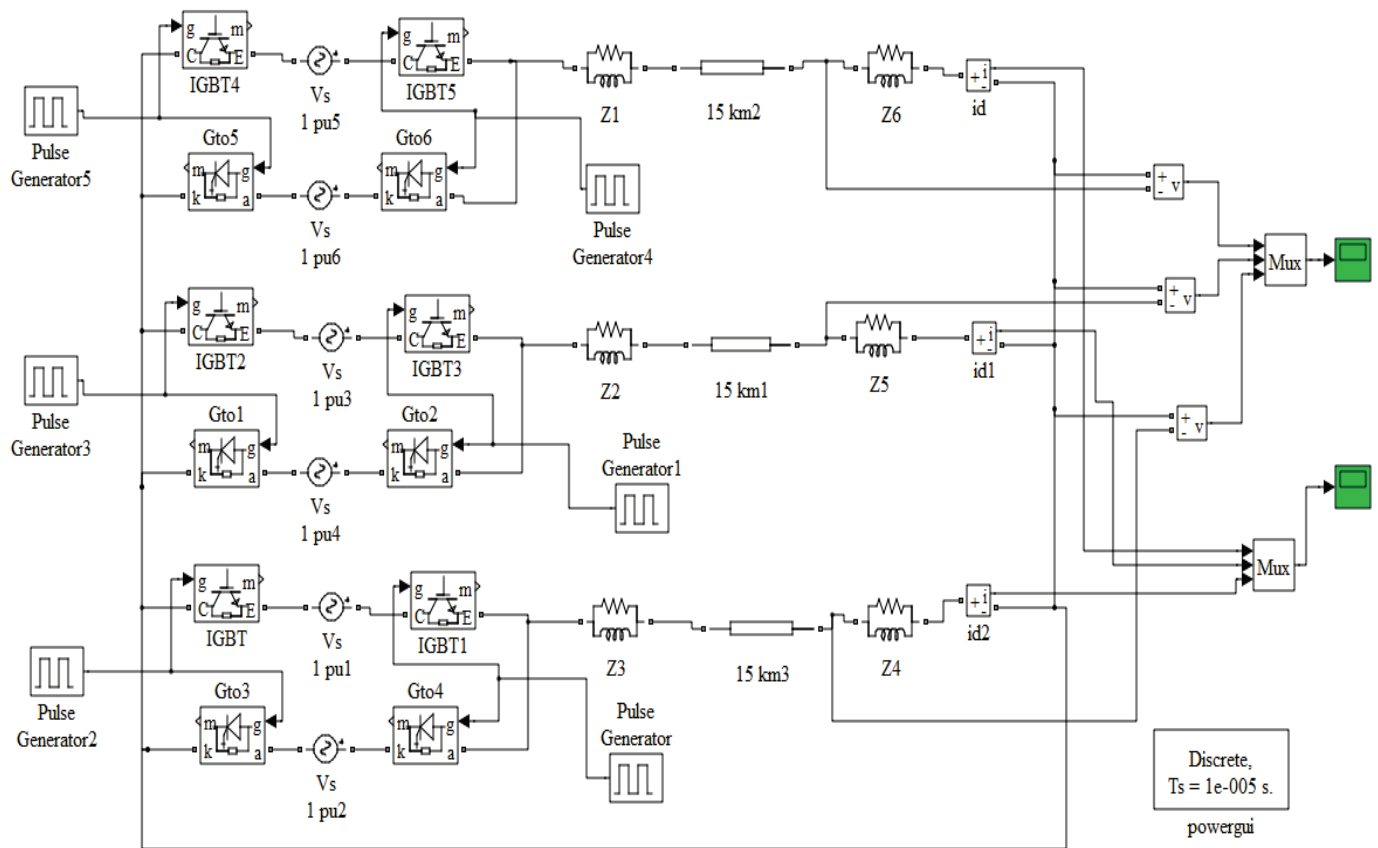
Figure 7 Regulated power line of 15 km

For the impedance of 0.9Z at Tab. 4, a compensation power of 880 VA and a balancing current of 4 A are provided with a 0.89 *MCI* value when a compensation power of 968VA and a balancing current of 8.8 A are provided with a 0.99 of *MCI*. The first greatest balancing power and current are 3872 VA and 8 A that are provided

with 0.99 of *MCI* at the 0.6Z of impedance, while the second greatest balancing power and current are 2904 VA and 13.2 A that are provided with 0.99 of *MCI* at 0.7Z of the impedance. As the unbalanced phase impedance decreases, the applied *MCI* and the balancing current increase, which leads to an increase in the balancing power. When the

impedance value (Z) is 10 ohm, the balancing current and power cannot be provided with 0.6 of modulation index to the system supplied with 330 V for 0.5Z and 0.4Z impedance values. In line with the model in Figure 1, a line length of 15 km in Fig. 7 can be obtained if a serial RLC circuit is added to the series. Z1 = Z2 = Z3 = Z4 = Z5 = Z6 = 10 + j0.1.

R, L, C values for the impedance of the line (Z_w) are respectively as 0.143 ohm, 102×10^{-2} H, $C = 1510 \times 10^{-8}$. Regulated power line of 15 km is in Fig. 7.

Parallel RL loads connected in series at the beginning and end of the 15 km long line in Fig. 7 are energized by alternating power sources that are controlled by switches with 0.9 of modulation index. The three-phase alternating voltage that occurs at the end of the power line is as in Fig. 8a, while the harmonic distortion of the voltage on the load is as in Fig. 8b.
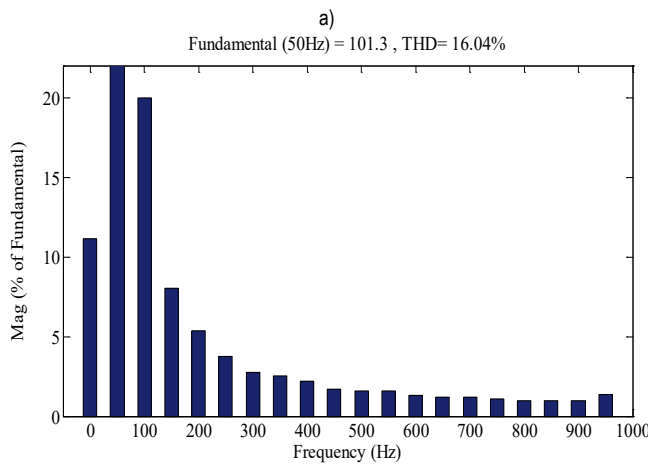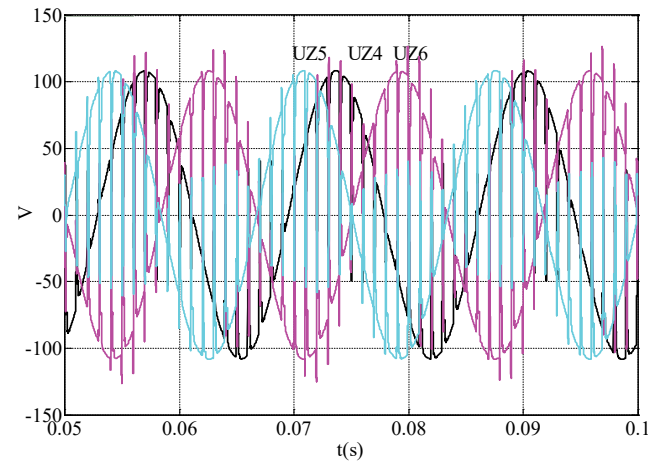

a)

Fundamental (50Hz) = 101.3 , THD= 16.04%

b)

Figure 8 a) The three-phase alternating voltage that occurs at the end of the line, b) the harmonic distortion of the voltage on the load

On the power line, 101 volts of the alternating voltage at the maximum value is formed on loads. The effective value of the voltage is 90.9 V because the modulation index is 0.9. Although there is no filtering element on the line, the distortion of the load voltage is 16%. If the load on such a line is provided with alternating voltage by conventional inverter methods, this value will exceed 100%. When

Parallel RL loads connected in series at the beginning and end of the 15 km long line are energized with alternating source, a three-phase alternating current that occurs on the load is presented in Fig. 9.
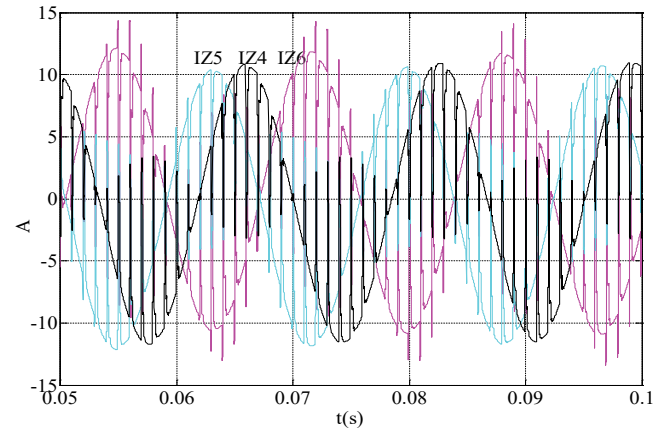

Figure 9 A three-phase alternating current of the 15 km long line

On the power line, a 12-volt alternating current at the maximum value is formed on loads. The effective value of the voltage is 10.2 A because the modulation index is 0.9. According to the results, the power distribution line is simulated for efficient power distribution and control without losing a lot of time and money. By taking this model into consideration, applications can be performed in less time and with less error rate. As the missing and difficult sides of the power line in the simulation can be determined, the accidents and errors that may occur are reduced, and the loss of life and property is eliminated.

4 CONCLUSION

The paper presented power control by inverse half rectifier processing method at energy distribution line in the simulation. The three-phase power line was controlled by semiconductor switches in reverse and parallel connected sources for each phase. First, the circuit model and mathematical equations of the line were created. In mathematical equations, the effect of the modulation index of the control signals applied to the switches to the power occurring on the load was shown. In unbalanced loads, it was shown how to calculate the values of *MCI* to equalize the effective value of the current. The current and voltage of the line were measured at different loads in the line. The balancing current and power were calculated by measuring for different modulation indices and line impedances. Obtained results and the effect of modulation index on the results were discussed. Unbalanced load current imbalances were eliminated by equalizing the effective values of the currents. As the unbalanced phase impedance decreases, the applied *MCI* and the balancing current increase, which leads to an increase in the balancing power. According to the results obtained, the design and application of the line has been successfully achieved.

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