Harmonic Mitigation in High Power DC Drive System Using Current Injection Technique

S. Parthasarathy, V. Rajasekaran, and R. Sathishkumar

***Abstract*—The development of a simulation platform for the study and conception of current injection technique to improve power factor, to reduce current harmonics generated by a DC drive in high power application is discussed. This work proposes the simultaneous current injection in all the three phases. Two current shaping networks and current injection devices are applied for harmonic reduction and power factor improvement. Based on the simulated results, optimal current shaping network, current injection device, and firing angle are recommended. The work is carried out for converter at different firing angles and is simulated using MATLAB.**

***Index Terms*—Converter, current injection, harmonics, total harmonic distortion.**

I. Introduction

POWER quality problems are caused by significant increase of non linear loads such as variable speed AC and DC motor drives, uninterruptible power supplies (UPS), magnetic power supplies, and high power induction heating equipment etc. The interface of converters to the electric utility exhibits nonlinear characteristics with poor input power factor. Further, switching devices cause significant harmonic currents in the utility lines resulting with increased distortion, malfunctioning of equipment, and increased losses.

Harmonic current mitigation in DC drive (thyristor controlled rectifier) can be achieved by injection of third harmonic current. The current injection system consists of a current injection network and a current injection device. The network that provides current injection is connected parallel to the load. The third harmonic current injection provides the reduction of input current total harmonic distortion (THD_I). A current injection network [1]-[3] and a current injection device [4], are combined to reduce the input current THD. When these two units are analyzed, they are connected to the three-phase converters at all five of its terminals, providing a link between the thyristor bridge output and the input. The purpose of these two units is to shape the input currents and to reduce their THD values. The current injection device divides the current supplied by the current injection network into three equal parts and injects them back to the supply lines.

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A current injection device consists of zigzag auto transformer, two single phase transformers [3] with required volt-ampere rating. To minimize the THD of the input currents, the injected current should be in phase with the harmonic component of the rectifier output terminal voltages, at the triple of the line frequency. The current taken by current injection network from the rectifier output terminals should be equal to three quarters of the output current. Here two types of current injection networks have been discussed. Based on the results, optimal current shaping network and current injection devices are recommended. This work is carried out for DC drive system. The DC drive is loaded up to 1.119 MW, and simulated with the help of MATLAB Simulink with different firing angle.

II. Principle of Current Injection

Reduction of total harmonic distortion in thyristor controlled rectifier can be achieved by a combination of current injection network and current injection device shown in Fig. 1. The function of these two units is to shape the input currents and to reduce their THD values [1]-[3].

Let us assume that the rectifier is supplied by a symmetric undistorted three-phase voltage system, [2]

$$v_p = v_m \cos(\omega_o t - (p-1)\frac{2\pi}{3}) \tag{1}$$

where v_m = maximum voltage and $p = 1, 2, 3$.

The ultimate goal is to achieve pure sinusoidal input currents in phase with the corresponding phase voltages

$$i_p = i_m \cos(\omega_o t - (p-1)\frac{2\pi}{3}) \tag{2}$$

where i_m = maximum current and $p = 1, 2, 3$.

The current injection device divides the current supplied by the current injection network into three equal parts and injects them back to the supply lines

$$i_{x1} = i_{x2} = i_{x3} = i_x = \frac{1}{3} i_y \tag{3}$$

To reduce the THD of the input currents, the main obstacles faced are the gaps in the input currents which are present during the time intervals, when the phase is reverse biased. In terms of the diode state functions, these intervals are described in [3].

III. Overview of Current Injection Network

The total harmonic distortion of the input currents are minimized only when the injected current is in phase with harmonic component of a rectifier output terminal voltages at the triple of line frequency. The third harmonic current taken from the current injection network is equally divided

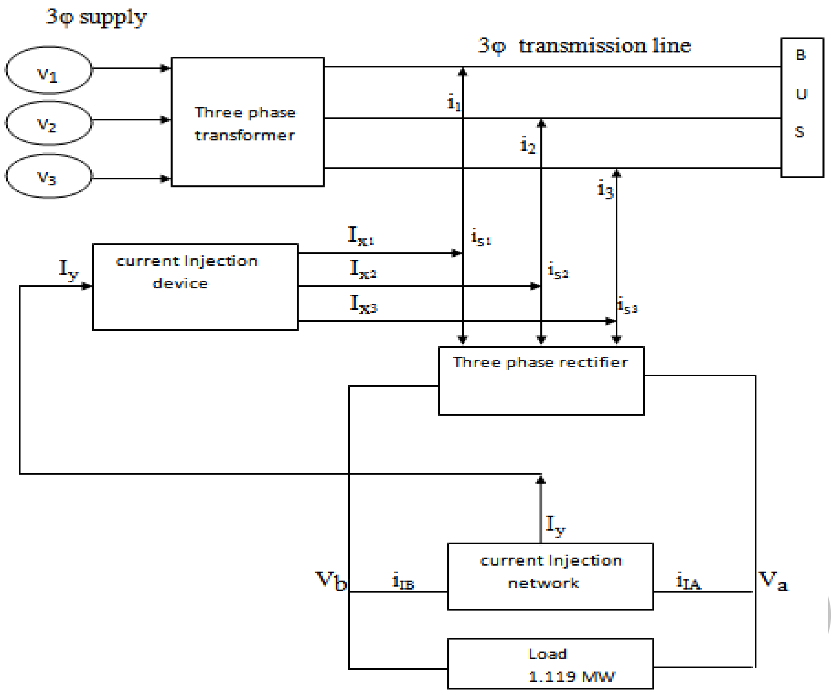


Fig. 1. Three phase rectifier with current injection.

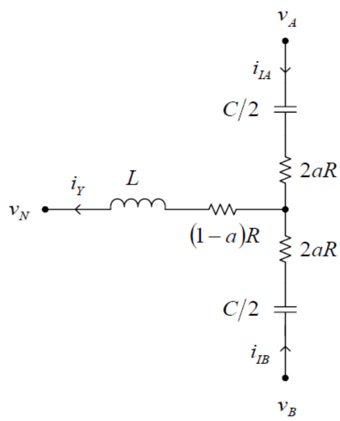


Fig. 2. Current injection network A.

into three parts by the current injection device. The current injection network should be as simple as possible and inexpensive. Two current injection networks A and B are proposed in [3].

The circuit diagram of the current injection network A is shown in Fig. 2, which consists of two capacitors, an inductor, and three resistors [3]-[9].

The current injection network B shown in Fig. 3 has two additional inductors whereas the current injection network A contains one.

The $(1-a)$ R resistor in the current injection network model is made in order to include losses in the current injection device model. This resistor is solely responsible for the amplitude and the phase of the injected current [3], [10]-[14]. The resistance parameter "a" is within the limits $0 < a < 1$. The output terminal voltages v_A and v_B are shown in Fig. 3.

IV. Overview of Current Injection Device

The current injection device is a part of current injection technique and it divides the current supplied by current injection network into three equal parts and injects them back to the supply lines [3]-[6]

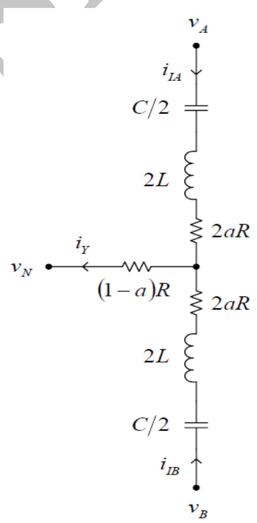


Fig. 3. Current injection network B.

$$i_{x1} = i_{x2} = i_{x3} = i_x = \frac{1}{3} i_y \tag{4}$$

$$v_N = \frac{1}{3}(v_1 + v_2 + v_3) = 0 \tag{5}$$

The recommended current injection devices are zigzag-autotransformer, two single phase transformer, three phase inductor and WYE-WYE connected transformer [3]. In this paper, zigzag auto transformer and two single phase transformers have been proposed as current injection device as shown in Fig. 4.

The two single phase transformers T1 and T2 are assumed as ideal transformer models, i.e., having perfect coupling and negligible magnetizing currents and are shown in Fig. 5.

The first of the transformers, labeled T1, divides the injected current i_Y in the ratio 2:1, result of which satisfies one third of the first current injection device requirement (4).

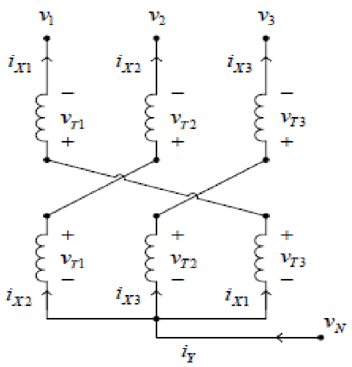


Fig. 4. Zig-zag auto transformer.

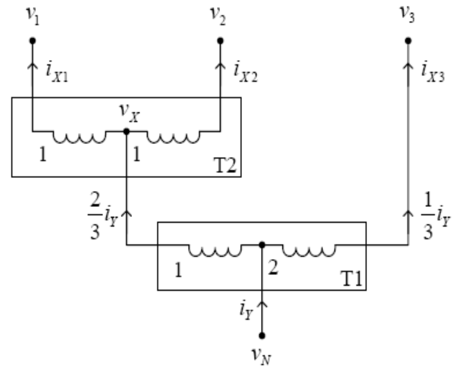


Fig. 5. Two single-phase transformers.

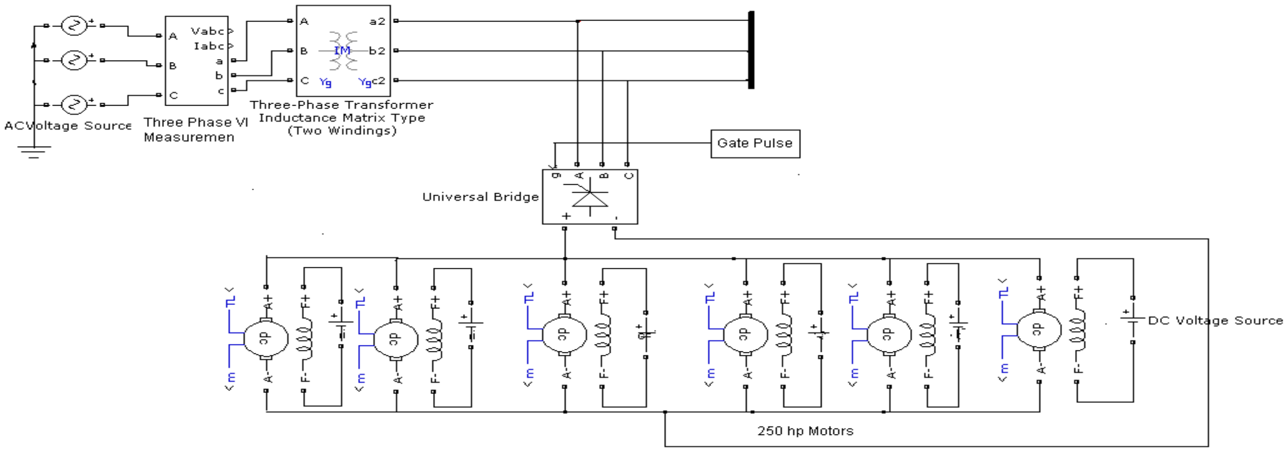
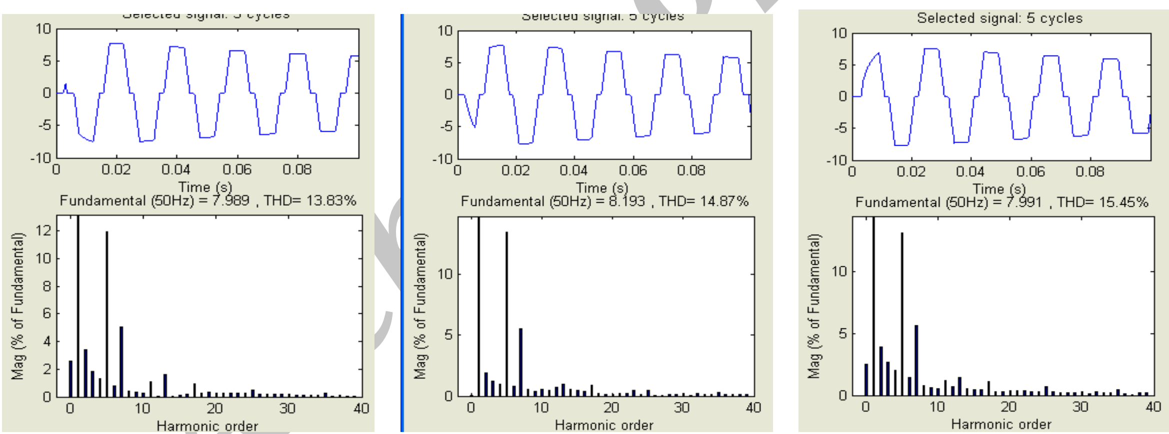


Fig. 6. Simulated circuit for rectifier without current injection.



(Phase A) (Phase B) (Phase C)

Fig. 7. Distorted three phase input current wave with harmonic spectrum for rectifier without current injection.

V. Case Study

In this proposed simulation work, a high power rectifier is acting as a harmonic producing non linear load which is connected to a 220 kV, 50 HZ three phase high voltage AC (HVAC) supply line. A 250 kVA transformer is used to step down the voltage from 220 kV to 110 kV, the rectifier is connected to six 250 hp motors. The motors are loaded up to 1.119 MW.

The simulation work is carried out by using two networks network A and network B for both the injection devices zigzag auto transformer and two single phase transformers.

For the supply voltage of 110 kV, the network parameters like resistor (R), inductor (L), and the capacitor (C) values are calculated based on the design formulae [3].

A. Simulated Results for Rectifier without Current Injection

The Fig. 6 shows the simulated circuit for rectifier without current injection. The rectifier is loaded with six 250 hp separately excited DC motors. The simulation work is to be carried out for different firing angles by varying the gate pulses given to the rectifier system. Due to non linear behavior of the rectifier, the three phase input current gets highly distorted.

The MATLAB Simulink powergui block gives a distorted wave and its harmonic spectrum is shown in Fig. 7 for the firing angle (α) of 45°. It is observed that THD_I is 13.83%, 14.87%, and 15.45% in the phases A, B, and C respectively. The 5^{th} and 7^{th} order of harmonics are dominant than the other order of harmonics

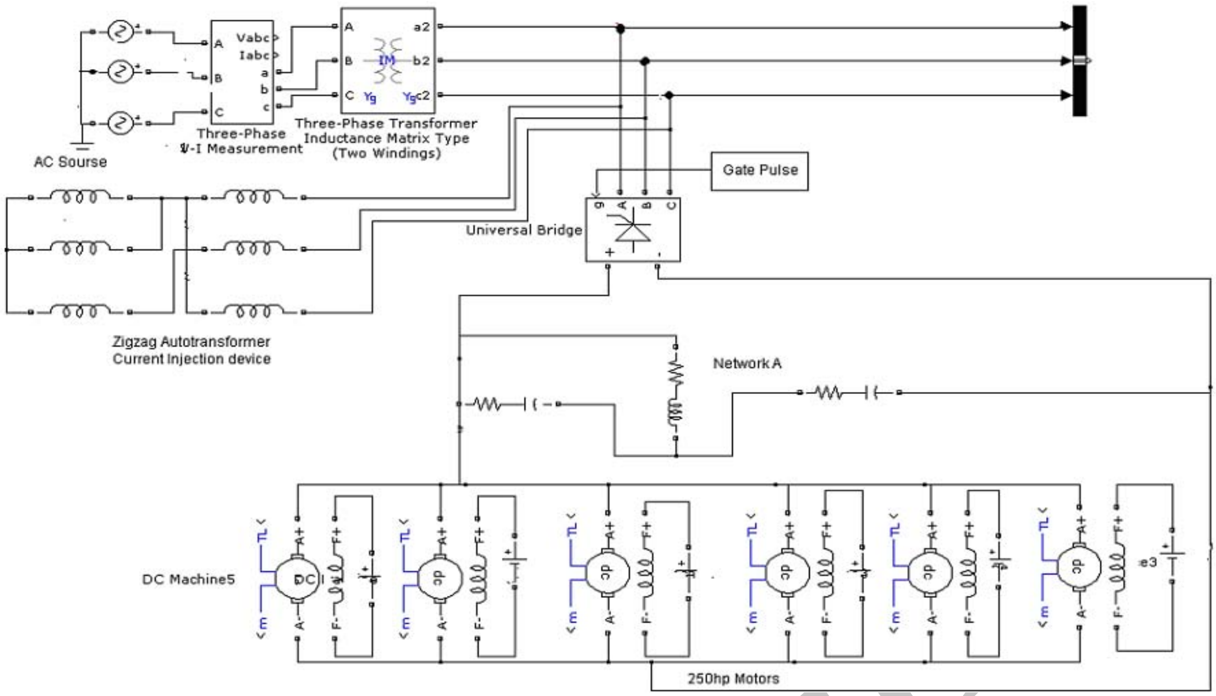
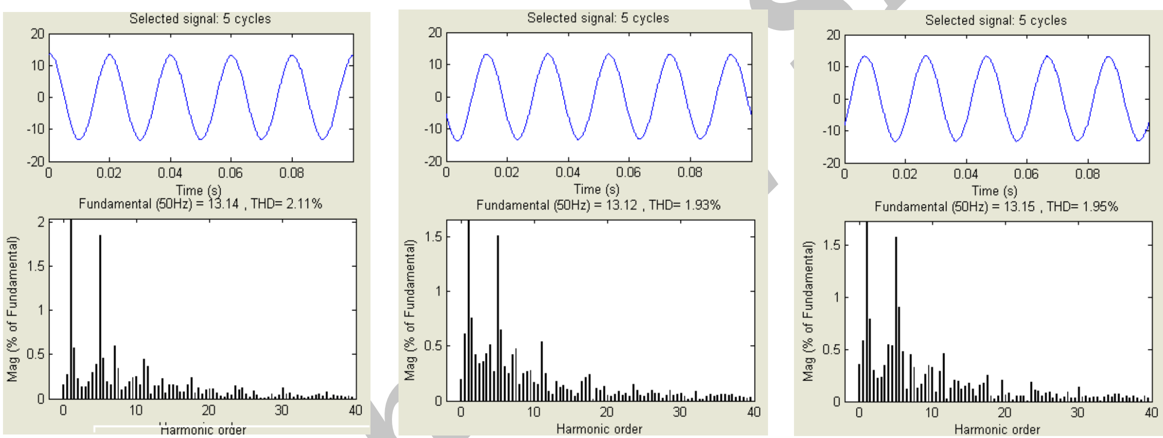


Fig. 8. Simulated circuit for rectifier with current injection using network A with zig-zag auto transformer.



(Phase A) (Phase B) (Phase C)

Fig. 9. Three phase input current wave and harmonic spectrum for rectifier with current injection using network A with zig-zag auto transformer.

for the system. It is clear that THD_I values for all the three phases are violating the harmonic standard specified by IEEE 519-1992.

B. Simulated Results for Rectifier with Current Injection

Fig. 8 shows the simulated circuit for rectifier with current injection by using network A and zig-zag auto transformer as the current injection device. Here the injected current is to be taken with the help of network A and to be divided equally three parts by using zig-zag auto transformer.

These divided current are injected into the input of the rectifier system. This injected current is to shape the distorted input current and to reduce their THD_I values. The harmonic spectrum and the rectifier input current waves are shown in Fig. 9. It is observed that the THD_I is reduced to 2.11%, 1.93%, and 1.95% in phases A, B, and C respectively and also the rectifier input current wave form is almost sinusoidal.

Fig. 10 depicts the simulated circuit for the rectifier with current injection with the help of same network A, but, two single transformers is used as the current injection device.

Fig. 11 is the resultant input current wave and harmonic spectrum. The THD_I values for all the three phases are 1.55%, 1.80%, and 1.72%.

Fig. 12 is the simulated circuit for a rectifier system, which uses network B and a zigzag auto transformer as the current injection device. Its input wave and harmonic spectrum are shown in Fig. 13. In this case, the THD_I values are 2.13%, 2.13%, and 2.00%.

The Fig. 14 is the simulated circuit for rectifier with current injection using network B and two single phase transformer as injection device. The simulated results are taken for the same 45° firing angle, is depicted in Fig. 15. The dominant 3rd and 5th order of harmonics are greatly suppressed by this current injection technique. The input current wave has less distortion and THD_I values are 1.53%, 1.67%, and 1.64%. These values are lower than the previous cases.

VI. Power Factor vs Harmonic Reduction

Assuming an ideal sinusoidal input voltage source, the power factor can be expressed as the product of the distortion factor and the displacement factor, as given in

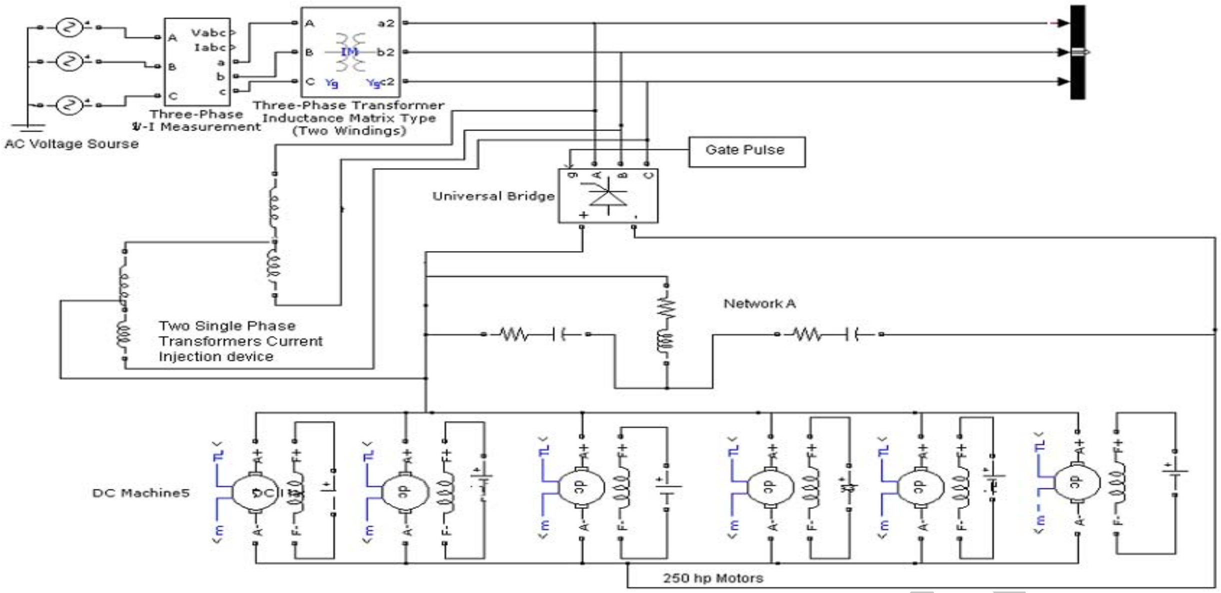
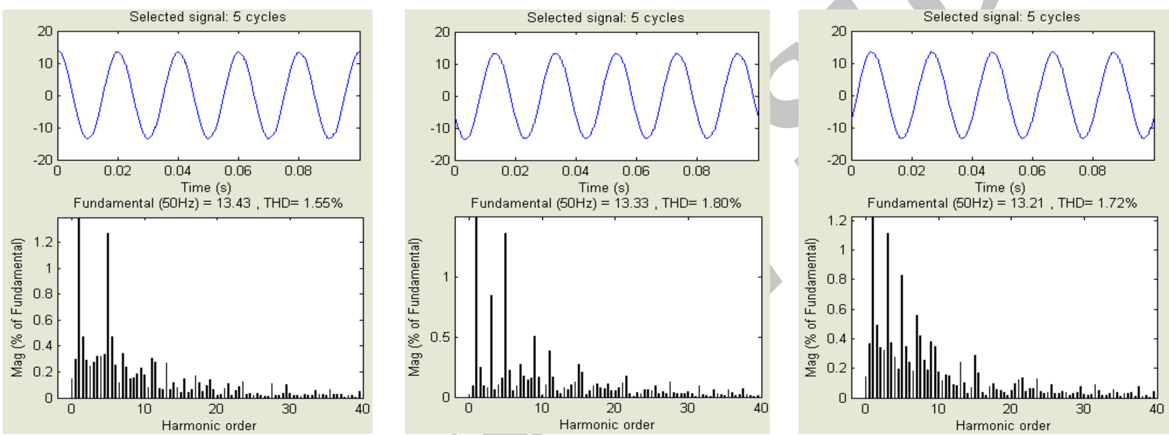


Fig. 10. Simulated circuit for rectifier with current injection using network A with two single phase transformer.



(Phase A) (Phase B) (Phase C)

Fig. 11. Three phase input current wave and harmonic spectrum for rectifier with current injection using network A with two single phase transformer.

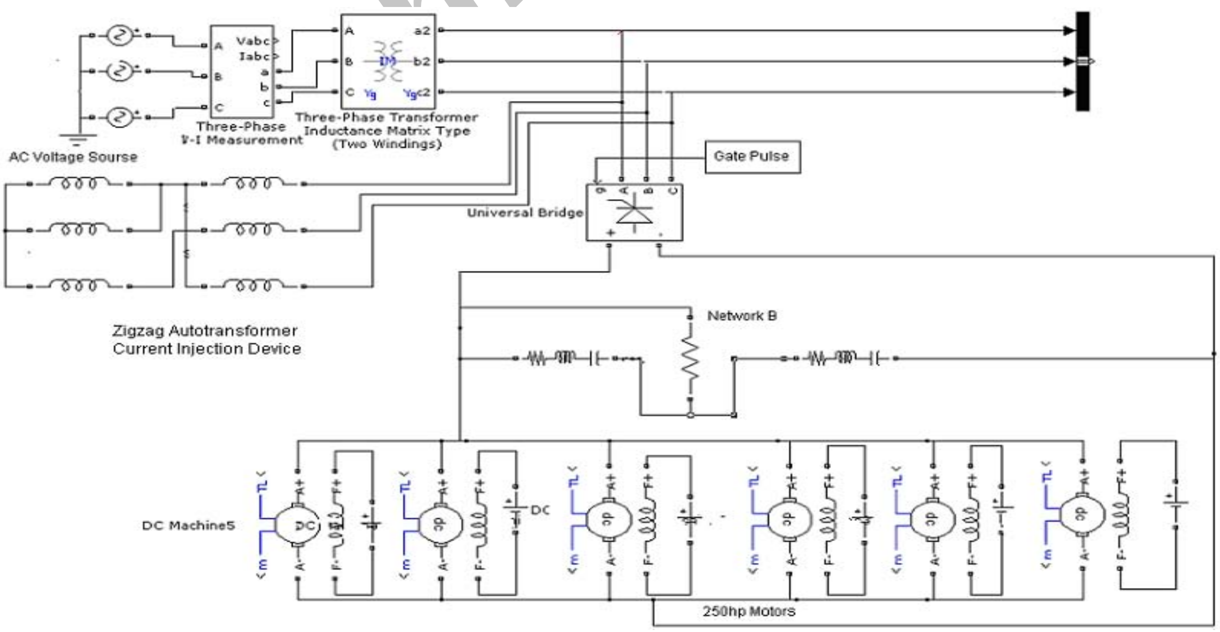
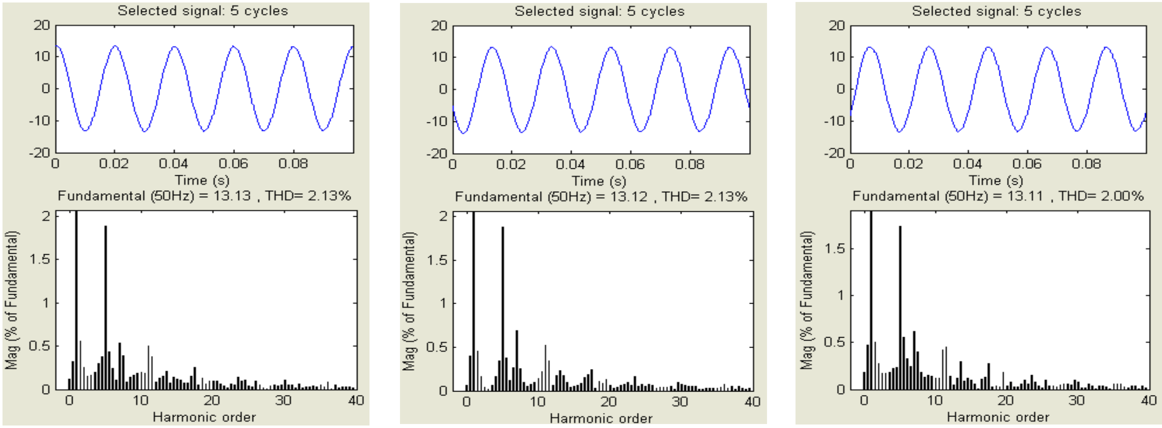


Fig. 12. Simulated circuit for rectifier with current injection using network B with zig-zag auto transformer.

(6) and (7). The distortion factor K_d, is the ratio of the fundamental root mean-square (RMS) current $(I_{rms(1)})$ to the total RMS current (I_{rms}). The displacement factor k_θ is the cosine of the displacement angle (φ) between the fundamental input current and the input voltage [15]

$$Power\ Factor(PF) = K_d K_\theta \tag{6}$$



(Phase A) (Phase B) (Phase C)

Fig. 13. Three phase input current wave and harmonic spectrum for rectifier with current injection using network B with zig-zag auto transformer.

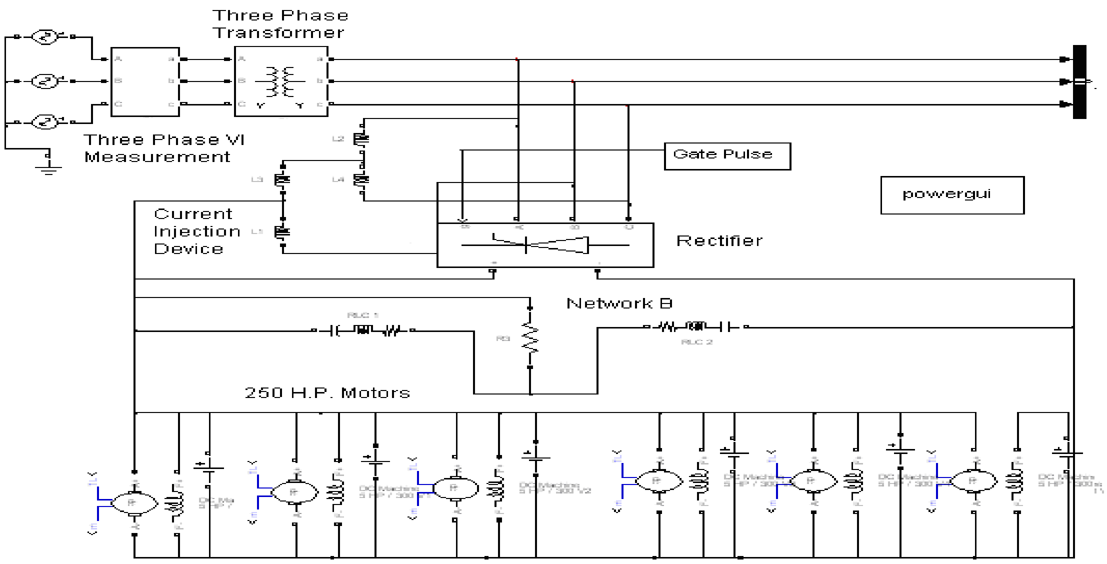
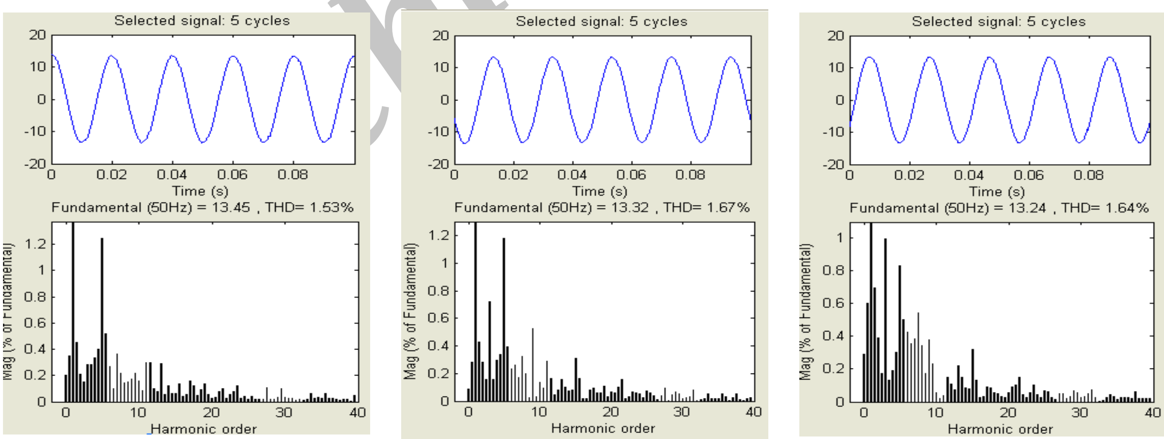


Fig. 14. Simulated circuit for rectifier with current injection using network B with two single phase transformer.



(Phase A) (Phase B) (Phase C)

Fig. 15. Three phase input current wave and harmonic spectrum for rectifier with current injection using network B with two single phase transformer.

$$PF = \frac{V_{rms} I_{rms} \cos\phi}{V_{rms} I_{rms}} = \frac{I_{Lrms} \cos\phi}{I_{rms}} = K_d \cos\varphi \qquad (7)$$

The distortion factor K_d and displacement factor K_θ are given by (8) and (9) respectively

$$K_d = \frac{I_{rms(l)}}{I_{rms}} \qquad (8)$$

$$K_\theta = \cos\varphi \qquad (9)$$

The displacement factor K_θ can be made unity with a capacitor or inductor, but making the distortion factor K_d unity is more difficult. When a converter has less than unity power factor, it means that the converter absorbs apparent power higher than active power. It shows that the power source has a higher VA rating than the load needs. In addition, the harmonic currents generated by the converter in the power source affect other equipments. The following (10) and (11) relate total harmonic distortion with power factor [15].

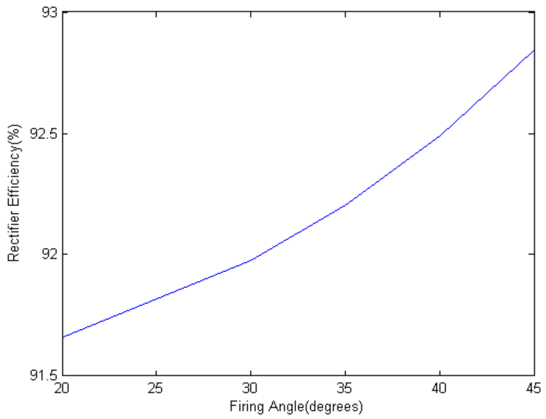


Fig. 16. Rectifier efficiency vs firing angle (α°)

TABLE I
COMPARISON OF THD_I FOR RECTIFIER WITHOUT CURRENT INJECTION

Injection device's	Without injection (THD_I)		
Firing angle (α°)	A	B	C
$\alpha = 20$	13.65%	14.32%	14.43%
$\alpha = 30$	13.68%	14.50%	14.74%
$\alpha = 35$	13.71%	14.61%	14.93%
$\alpha = 40$	13.76%	14.73%	15.18%
$\alpha = 45$	**13.83%**	**14.87%**	**15.45%**
Power factor $(\alpha = 45^{\circ})$	0.99057	0.98912	0.98827

TABLE II
COMPARISON OF THD_I FOR RECTIFIER WITH CURRENT INJECTION NETWORK A

Injection device's		With injection network A					
		Two single phase transformers			Zig-zag auto transformers		
Firing angle (α°)	Rectifier efficiency (%)	THD_I A	B	C	A	B	C
$\alpha = 20$	91.65	1.60%	1.82%	1.76%	2.14%	1.91%	2.04%
$\alpha = 30$	91.97	1.58%	1.81%	1.74%	2.13%	1.91%	2.01%
$\alpha = 35$	92.20	1.57%	1.81%	1.73%	2.12%	1.92%	1.99%
$\alpha = 40$	92.49	1.56%	1.81%	1.73%	2.12%	1.93%	1.97%
$\alpha = 45$	**92.51**	**1.55%**	**1.80%**	**1.72%**	**2.11%**	**1.93%**	**1.95%**
Power factor $(\alpha = 45^{\circ})$		0.9998	0.9998	0.9998	0.9997	0.9998	0.9998

TABLE III
COMPARISON OF THD_I FOR RECTIFIER WITH CURRENT INJECTION NETWORK B

Injection device's		With injection network B					
		Two single phase transformers			Zig-zag auto transformers		
Firing angle (α°)	Rectifier efficiency (%)	THD_I A	B	C	A	B	C
$\alpha = 20$	91.70	1.59%	1.72%	1.71%	2.15%	2.12%	2.10%
$\alpha = 30$	92.00	1.57%	1.70%	1.68%	2.14%	2.12%	2.06%
$\alpha = 35$	92.20	1.56%	1.69%	1.66%	2.14%	2.12%	2.04%
$\alpha = 40$	92.50	1.54%	1.68%	1.65%	2.13%	2.13%	2.02%
$\alpha = 45$	**92.87**	**1.53%**	**1.67%**	**1.64%**	**2.13%**	**2.13%**	**2.00%**
Power factor $(\alpha = 45^{\circ})$		0.999	0.9998	0.999	0.999	0.999	0.9998

$$THD(\%) = 100 \times \sqrt{(1/K_d^2) - 1} \qquad (10)$$

$$K_d = \frac{1}{\sqrt{1 + (THD(\%)/100)^2}} \qquad (11)$$

therefore, when the fundamental component of the input current is in phase with the input voltage, $K_\theta = 1$ and

$$PF = K_d K_\theta = K_d \qquad (12)$$

Equation (13) shows the relation between the power factor and harmonic distortion [15]

$$Power\ Factor = \frac{1}{\sqrt{1 + (THD(\%)/100)^2}} \qquad (13)$$

VII. RECTIFIER EFFICIENCY

Optimal amplitude and phase of the injected current are derived in order to minimize the input current total harmonic distortion (THD) as well as to improve the efficiency of the rectifier [3].

The power taken by the current injection network is

$$P_{INJ} = (3\sqrt{3}/8\pi) V_m I_{OUT} k \cos\varphi \qquad (14)$$

The rectifier provides the output power

$$P_{OUT} = V_{OUT} I_{OUT} = (3\sqrt{3}/\pi) V_m I_{OUT} \qquad (15)$$

The input power of the rectifier is the sum of the output power and the power taken by the current injection network

$$P_{IN} = P_{OUT} + P_{INJ} \qquad (16)$$

Assuming the power taken by the current injection network is dissipated, the rectifier efficiency is equal to [3]

$$\eta = P_{OUT}/(P_{OUT} + P_{INJ}) \qquad (17)$$

Based on the (14) to (17) the rectifier efficiency is calculated and the efficiency graph as shown in Fig. 16 drawn for different firing angle (α°).

Table I shows the comparison of THD_I for the high voltage rectifier system without current injection networks and injection devices with different firing angles and power factor for the firing angle of 45°.

Table II and III shows the comparisons of THD_I and efficiency for the high voltage rectifier system with current injection networks A and B respectively with the power factor of 45° firing angle.

VIII. Conclusion

In this paper a current injection technique has been suggested to a high power DC drive system, in order to improve power factor and to reduce the harmonics, loaded up to the power of 1.119 MW. The current injection technique is analyzed and it shows that it is possible to obtain ideal sinusoidal waveforms of the input currents in phase with the corresponding input voltages. Two current shaping networks and current injection devices are proposed for the rectifier system, with various firing angles. Based on the simulation results, the tabulations are made for total current harmonic distortion (THD_I) and power factors. The results are compared, with and without current injection networks and the current injection devices. It is evident that 45° is the appropriate firing angle for the proposed rectifier system and it proves that the network B with the injection device of two single phase transformer is suitable for the proposed system. It improves the power factor and rectifier efficiency, and also reduce the total harmonic current distortion (THD_I) which obeys the harmonic limit standard of IEEE 519-1992.

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