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Performance Evaluation of DC Motor Using 12 Pulses Three phase Controlled Rectifier Assisted with Auxiliary Supply Voltage

Mahendra Singh Rajput[1], Arun Pachori[2]

[1]Electrical Engineering Department, Jabalpur Engineering College, Jabalpur (M.P), India
[2]Associat prof., Electrical Engineering Department, Jabalpur Engineering College, Jabalpur (M.P), India

Abstract: **This paper deals with the 12 pulse convertor for rectification process. Three-phase thyristor rectifiers have been used in industries for obtaining a variable dc voltage, but the lower order harmonics are the major problem present in the input currents of these systems. 12-pulse convertor configuration is very useful in high power applications, but the (12*m* ± 1)th (*m*: integer) harmonics are still presents in the system. Thus this paper proposes the further reduction in harmonics using auxiliary supply and analyses the performance of a dc motor supplied by the 12 pulse convertor with auxiliary voltage supply assisted.**

Keywords: **AC–DC power conversion, power conversion harmonics, power electronics, thyristor applications, thyristor converters.**

I. INTRODUCTION

Generally, diode and phase controlled rectifiers are used for conversion of single phase or three phase power from ac-to-dc or vice-versa. Since the commutation or turn of process takes place at the zero crossing of the current, these are also called by “line commutated” rectifiers. These rectifiers are resilient and economical, but draw non sinusoidal currents or reactive power from the source, due to which the power quality of the system became progressively worse. To reduce the harmonic distortion generated by the rectifiers made by these rectifiers devices, passive linear filters or power factor correction structures can be employed [1–3]. The multi pulse three phase rectifiers overcome these issues by introducing phase shift by means of special three-phase transformers [4-5]. Moreover, the simplicity and reliability of the diode rectifiers are maintain to its original state. However, they are large and unwieldy.

For low and medium power drive applications three phase pulse width modulation (PWM) rectifiers are used where the requirements made by international standards should be satisfied [6–9]. These structures are the most promising rectifiers from a power quality viewpoint [10- 12] since they can present low harmonic distortion and unity power factor.

Recent trends introduce hybrid rectifiers for the rectification of three phase power in high-power conversion system as a new class of three-phase rectifiers, [13–15]. The term “hybrid rectifier” denotes the series and/or parallel connection of a line-commutated rectifier and a self-commutated converter. The line-commutated rectifier operates at low frequency and has a higher output power rating. The active rectifier is designed to operate with a small power rating and at a high switching frequency [16].

A convertor of 12-pulse [1], [5], [13]–[15] consisting of two sets of six-pulse rectifiers is used for high-power applications. This convertor diminishes the effect of fifth and seventh harmonic components produced by each of the two rectifiers, but the $(12m \pm 1)_{\mathrm{th}}$ (*m*:integer) harmonics still remain in the resultant input currents. It is usual to use passive power filters tuned to harmonics 11 and 13, and an additional high-pass filter to eliminate the remaining harmonics.

There are several configurations of 12-pulse thyristor rectifiers, but the method is applicable to only two configurations illustrated in Fig. 1(a) and (b). Fig. 1(a) is a parallel-connected choke-input type and Fig. 1(b) is a cascade connected capacitor-input type. Fukuda and Hiei applied this method to a cascade-connected 12-pulse thyristor rectifier [25] and revealed that the AVS was effective only in a narrow output voltage range. This is because the insertion of AVS to a 12-pulse rectifier is effective only if the dc current of the original six-pulse rectifier flows continuously. The dc current *i*rec1 or *i*rec2 in Fig. 1(b) with *Vi* = 0 flows continuously only in a very narrow firing angle range, say, α = 0–20◦ because the rectifier is of capacitor-input type. In contrast, the current *i*rec1 or *i*rec2 in Fig. 1(a) with V_i = 0 flows continuously in a wide firing angle range because the rectifier is of choke-input type.

A parallel-connected choke-input 12-pulse thyristor rectifier with an auxiliary voltage supply connected to each dc bus is considered in this paper, as shown in Fig. 1(a) to reduce the harmonics, especially the 11th and 13th components. It presents theoretical investigations on the principle of reducing the harmonics and a method to control the AVS voltage with respect to the load current and firing angle of the thyristors. It is shown that AVS is effective almost over a whole output voltage range.

Tanaka et al proposed the insertion of an interphase reactor with appropriate leakage inductance to the dc bus of a 12-pulse choke input type phase controlled rectifiers to reduce the harmonics at input side [26].

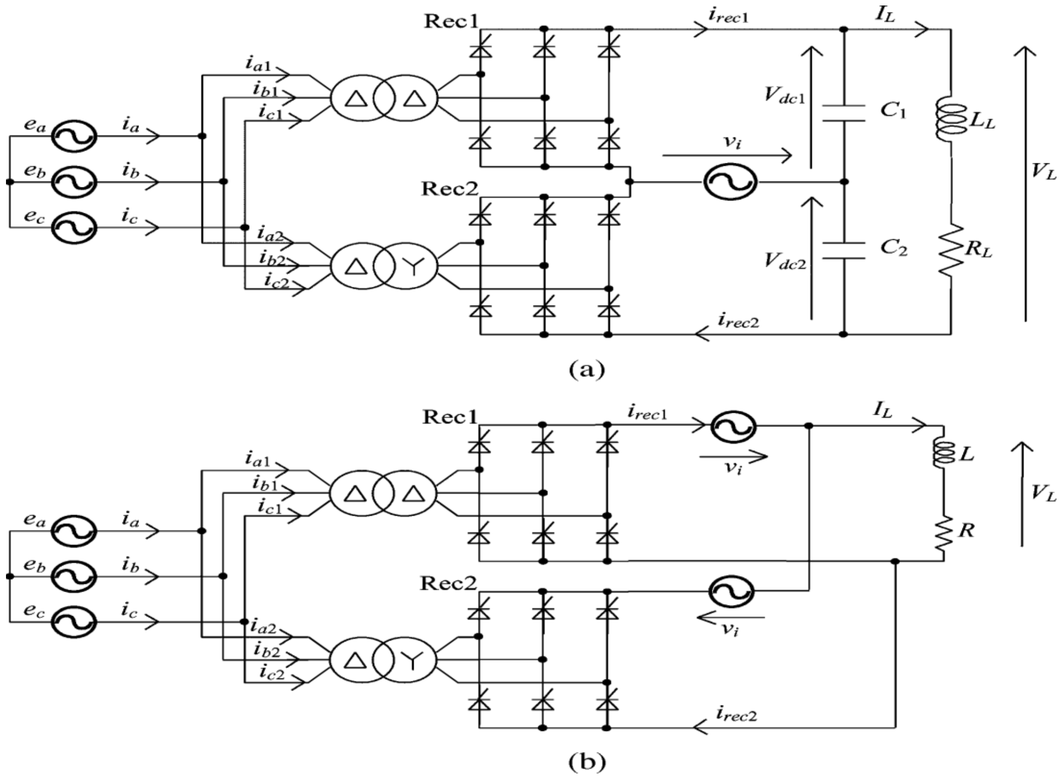

Fig.1. Configurations of phase-controlled 12-pulse thyristor rectifier with AVS v_i

(a) Choke-input type (b) Capacitor-input type

II. CIRCUIT CONFIGURATION AND OPERATION

Fig. 1(a) shows a phase controlled 12-pulse rectifier with AVSs proposed in this paper. It consists of two three-phase six pulse thyristor rectifiers, Rec1 and Rec2, connected in parallel; and two AVSs having a voltage *vi*. The input given to both rectifiers from identical two sets of three phase voltage source and phase displaced by 30^0 to each other. A conventional 12-pulse configuration includes an inter phase reactor in the dc circuit to equally share the dc currents *IL* in Rec1 and Rec2, but it is not necessary with the proposed configuration because i_{rec1} and i_{rec2} flow alternately.

Assume that the dc output currents $i_{rec1}$and i_{rec2}were triangular with a frequency six times that of the utility having a dc component *IL/*2, as shown in Fig. 2(a) and (b). Then, the input currents of the each rectifier, *ia*1 and *ia*2, and the resultant input current (*ia*= *ia*1 + *ia*2) would be as shown in Fig. 2(c)–(e), respectively. From the figure, one can observe that the harmonics almost disappear in *ia*. Total harmonic distortion (THD) of *ia* is as low as 1.06%.

A voltage source of voltage V_i is introduced in the circuit as auxiliary supply voltage source to shape the output current i_{rec1} and i_{rec2} of two rectifier circuit as indicated in Fig. 2(a)–(b). They are inserted in each dc bus of Rec1 and Rec2, as shown in Fig. 1(a) and generate a square-wave voltage with adjustable amplitude V_i. The AVS is synchronized with the switching of the *thyristors*, and has a frequency six times that of the main voltage, as shown in Fig. 2(f). In the figure, α denotes the firing angle of the thyristors and V_i changes its polarity synchronized with each communication instant of the thyristors.

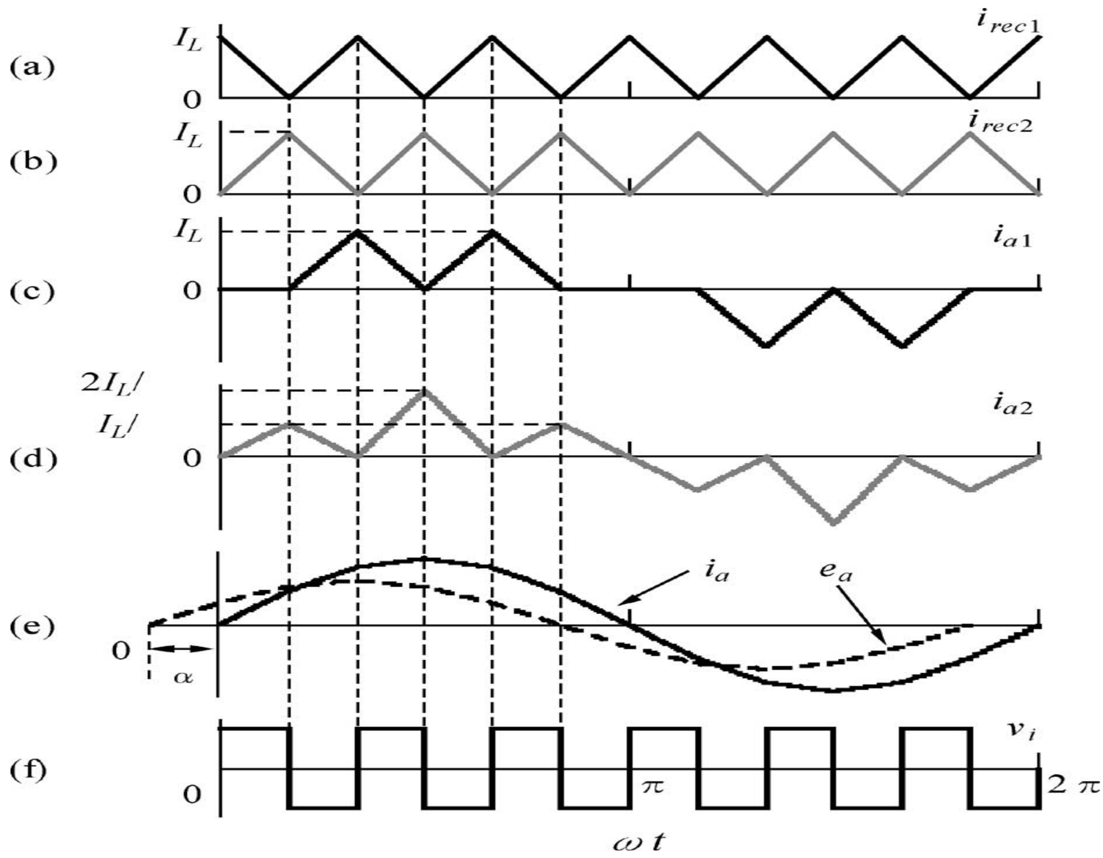

Fig. 2: Hypothetical 12-pulse rectifier current waveforms with AVS.

III. ANALYSIS OF OPERATION

The following two sets of three-phase main voltage systems, $e1$ and $e2$, defines the two rectifier systems Rec1 and Rec2, respectively. These are illustrated in Fig. 3.

$$e_{a1} = E\sin(\omega t + \tfrac{2\pi}{3}) \qquad e_{a2} = E\sin(\omega t + \tfrac{5\pi}{3})$$
$$e_{b1} = E \sin \omega t \qquad e_{b2} = E \sin\left(\omega t + \frac{\pi}{6}\right)$$
$$e_{c1} = E \sin\left(\omega t - \frac{2\pi}{3}\right) \quad e_{c2} = E \sin\left(\omega t - \frac{\pi}{2}\right)$$

Consider a time period, $\theta = \alpha$ *to* $\theta = \alpha + \pi/6$ with $\theta = \omega t$. The commutation in Rec2 starts at $\theta = \alpha$ from phase-$a2$ to phase-$b2$, and it finishes instantaneously as explained later. Fig. 4 gives the equivalent dc circuit, and the following equation holds.

$$2x\,\frac{d(irec1 - irec2)}{d\theta} = 2v_i - e_{11} + e_{22}$$

$$e_{11} \equiv (e_{a1} - e_{c1}),\;\; e_{22} \equiv (e_{b2} - e_{c2}) \qquad (1)$$

where $x = \omega l$ shows the leakage reactance of the transformer per phase, and $e11$ and $e22$ represent the instantaneous dc voltages of Rec1 and Rec2, respectively. Since the dc load current (IL= $i$rec1 + $i$rec2) is constant, the following equations hold.

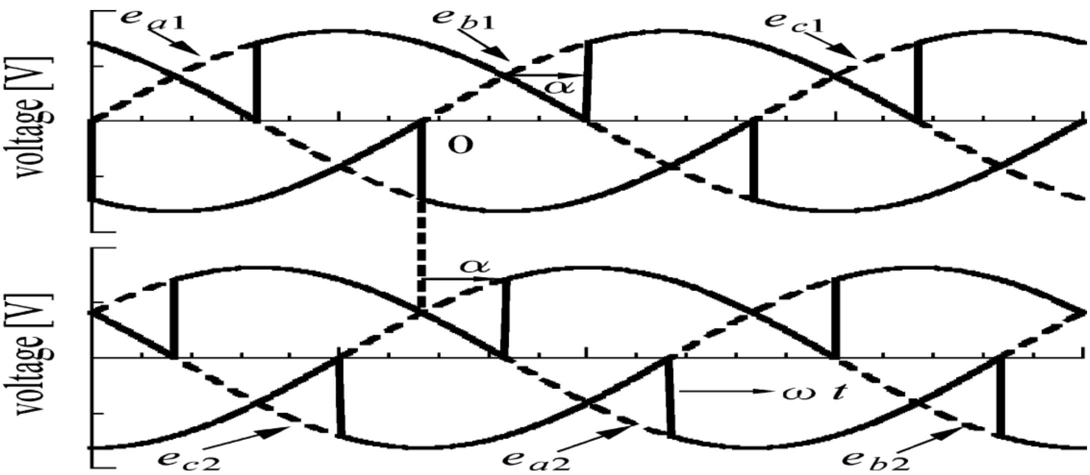

Fig. 3: Two sets of three-phase mains voltages, ea 1 − ec 1 for Rec1 and ea 2 − ec 2 for Rec2.

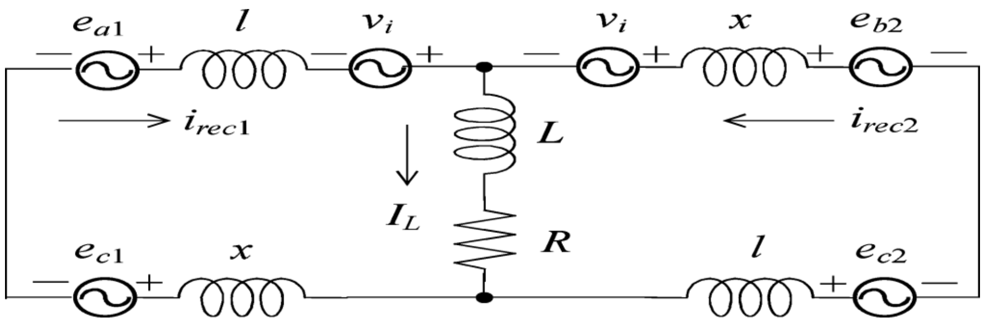

Fig. 4: Equivalent dc circuit during θ = α to α + π/6.

$$4x\frac{di_{rec2}}{d\theta} = V_s \qquad (2)$$

$$V_s \equiv 2v_i + 2\sqrt{3}\,E\left(\frac{\pi}{12}\right)\sin\left(\omega t - \frac{\pi}{12}\right) \qquad (3)$$

If the voltage VS is constant, (2) indicates that i_{rec1} increases linearly with time. Assume that the variations in i_{rec2} were as shown in Fig. 5, as indicated in Fig. 2(b). The initial condition would be $i_{rec1} = 0$ at $\theta = \alpha$, and the final condition would be $i$rec2 = IL at $\theta = \alpha + \pi/6$. Hence, the following relation is obtained.

$$V_s = \left(\frac{24}{\pi}\right)xI_L \qquad (4)$$

Similarly i_{rec1} decreases linearly with time in the same time duration, as shown in Fig. 5.

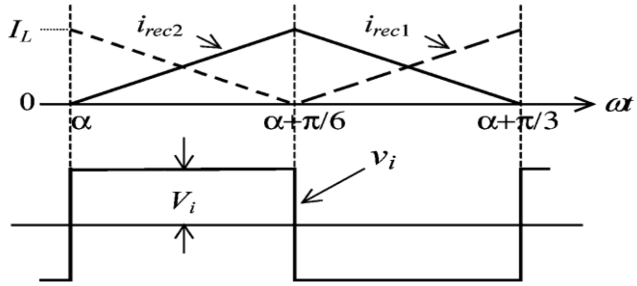

Fig. 5: Waveforms of dc output currents with AVS voltage V_i .

Thus, the output currents i_{rec1} and i_{rec2} of two rectifiers vary in a triangular shape due to AVS V_i indicated in Fig. 2(a) and (b), respectively.

For simplicity, assume that the second terms of *VS* in (3) is constant, averaging it over the period $\theta = \alpha$ to $\alpha + \pi/6$. Then, the amplitude of V_i will be given by

$$V_i = \left(\frac{12}{\pi}\right) x I_L - \left(\frac{6\sqrt{3}}{\pi}\right)\left(1 - \frac{\sqrt{3}}{2}\right) E sin\alpha$$

$$= \left(\frac{12}{\pi}\right) x I_L - 0.443 E sin\alpha \qquad (5)$$

During $\theta = \alpha + \pi/6$ to $\alpha + \pi/3$, the current i_{rec2} is forced to decrease from *IL* to 0, the right-hand side of (2) must be negative, −*Vs*. The average value of the second term of *Vs* in (3) is the same as that in the previous period but takes a negative sign. Hence, *Vi* should be a square wave with an amplitude *Vi*, and changes its polarity at every commutation instant of the thyristors. The commutation takes place at every 60◦ in Rec1 and Rec2 alternately. Thus, the frequency of Vi must be six times that of the main frequency. Equation (5) shows that the amplitude *Vi* should be controlled in relation to the load current *IL* and the firing angle *α*, to obtain best results in terms of harmonic distortion. It is interesting that there is a special combination between *IL* and *α*, which makes *Vi* = 0 or minimizes THD without AVS. This coincides with the conclusion in [26]. The following commutation starts at $\theta = \alpha + \pi/6$ in Rec1. It finishes immediately because i_{rec1} is already reduced to zero at that instant as Fig. 5 indicates. The thyristors commutate instantaneously.

IV. CHARACTERISTICS OF PROPOSED RECTIFIER

A. DC Output Voltage and Output Power

The average dc output voltage *VL*0 and output power *P*out of the rectifier will be

$$V_{L0} = \left(\frac{3\sqrt{3}}{\pi}\right) E cos\alpha \qquad P_{out} = \left(\frac{3\sqrt{3}}{\pi}\right) E I_L cos\alpha$$

At light load, if a higher instantaneous dc voltage is present at any of the rectifier Rec1 or Rec2 provides the dc current to the load for a very short period such as 30^0 after which the conduction stops but at heavy load, both rectifiers supply the dc current simultaneously, if AVS is not used otherwise if AVS is used, Rec1 and Rec2 provide the dc current simultaneously, but the current of commutating thyristor is reduced to zero at every commutation instant. The average dc voltage *VL*0 is exactly proportional to cos *α* because no current overlap occurs at thyristor commutation. Accordingly, the proposed rectifier provides a slightly lower dc average voltage than a conventional 12-pulse rectifier.

B. Volt–Ampere Rating of AVS

From (5), the amplitude of AVS *Vi* depends on *α* and *IL*. It is obvious that the maximum volt–ampere (VA) will occur at *α* = 0, because it provides the highest dc voltage and current. Thus, one has

$$V_i = \left(\frac{12}{\pi}\right) x I_L$$

Since rms values of the rectifier resultant input current *I* and the current flowing through AVS *Ii* are

$$I = \left(\sqrt{\frac{2}{3}}\right) I_L = 0.816 I_L \qquad I_i = \frac{I_L}{\sqrt{3}} = 0.577 I_L$$

The VA rating of AVS will be given by

$$VA_i = \left(\frac{12}{\pi}\right) x I_L I_i = \left(\frac{12}{\pi}\right) x_{pu} E \frac{I_L}{\sqrt{2}} = 3.82 x_{pu} E I_L$$

where *x*pu denotes the per-unit based leakage reactance of the transformer per phase. The ratio of the AVS rating to the rectifier output power will be

$$\frac{VA_i}{P_{out}(\alpha = 0)} = \left(\frac{4}{\sqrt{3}}\right) x_{pu} = 2.31 x_{pu}$$

If *x*pu = 2%, the VA rating of AVS would be less than 5% of the 12-pulse rectifier output.

It is noted that an interphase reactor is unnecessary with the proposed rectifier. It results in increasing the VA rating of AVS, because the inductance of an interphase reactor increases the reactance *x* in (1).

C. Auxiliary Voltage Supply

The author used a single-phase pulse width modulation (PWM) inverter illustrated in Fig. 6 for AVS with an adjustable output voltage. The AVS feeds voltage *vi* to Rec1 and Rec2 through a transformer having two identical secondary windings. The amplitude *Vi* is adjusted according to (5) depending

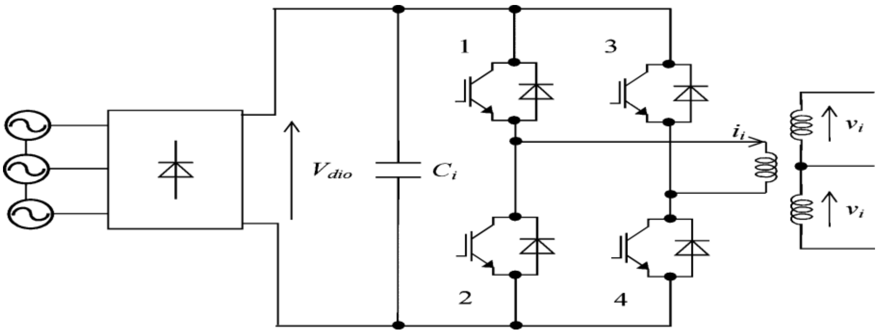

Fig. 6: Configuration of AVS.

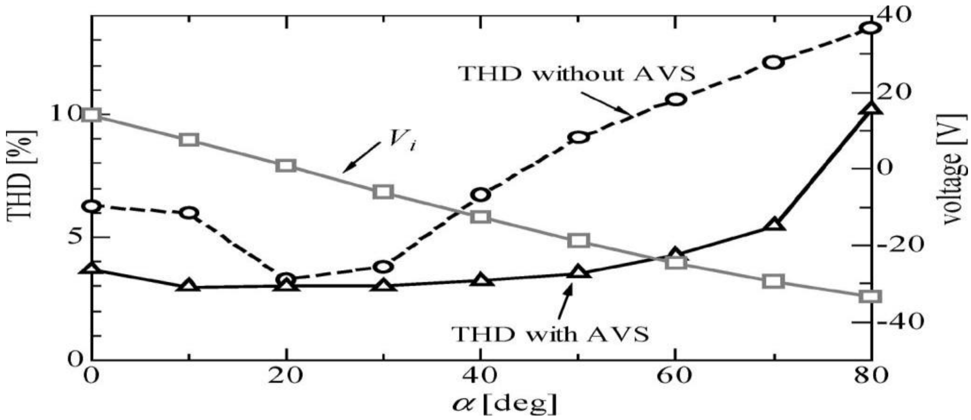

Fig. 7: Improvement in input current THD by inserting AVS with optimal amplitude.

on the load current *IL* and the firing angle *α*. The output power of AVS is calculated as

$$P_{iout} = \left(\frac{6}{\pi}\right)\int_{\alpha}^{\alpha+\pi/6} V_i(i_{rec1} - i_{rec2})d\theta = 0$$

There is no net power flow between the rectifier and AVS. The diode rectifier charges the dc capacitor *Ci* just at starting. Therefore, the input current of the diode rectifier at steady state would be zero if the capacitor *Ci* is large enough. Thus, it would not distort the mains currents. But, in practice, as some resistance components exist in the transformer windings, there is a slight power flow between the rectifier and AVS.

V. CONCLUSION

In this paper for the reduction of current harmonic distortion a 12-pulse choke-input phase controlled thyristor rectifier is used along with a single phase auxiliary square wave voltage supply. This paper proposed a current harmonic distortion reduction method for parallel-connected 12-pulse choke-input phase controlled thyristor rectifiers. The method employs a single phase square wave AVS and inserts it into the dc bus of the rectifier. This configuration enables one to reduce the harmonic distortion of the rectifier resultant input currents almost equivalent to that of a phase-controlled 24-pulse rectifier.

The principle of harmonic reduction especially in the 11th and 13th harmonics in the input currents, and presents how the AVS should be adjusted in relation to the load current and firing angle to get the best results in terms of harmonic reduction.

The most important application of this above proposed method is that it can be used as a drive to operate an electrical machine with reduced current harmonics. As a result with the help of reduction in current harmonics the efficiency and performance of our electric drives is improved to much better as compared to other methods.

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