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Research Paper

# A Novel Transformer-Based Single-to-Three Phase Conversion Technique Using Rotating Magnetic Field Theory

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**Abstract:** This paper presents a new single to three phase converter using rotating magnetic field transformer. Conventional transformers have been used in many converters aiming at supplementary improvements and they usually have no critical effect on the conversion technique. In this paper, the conversion technique is based on a special rotating magnetic field transformer in which there are two windings in the primary and six windings on the secondary side. In the proposed converter, first a single-phase voltage source is applied on the primary windings via a switching technique using thyristors to create a rotating magnetic field. Next, the created field induces three phase voltages on the secondary three phase windings. Nevertheless, the created field in the primary side suffers from low frequency harmonics and can be transmitted to the secondary three phase voltages. Hence, design of the secondary windings is modified to mitigate these harmonics. The paper discusses how the harmonics can be mitigated using two sets of three phase windings with appropriate shift. Finally, the proposed converter is modeled using state equations and the simulation results exhibit the effectiveness of the proposed converter.

**Keywords:** Air-Gap MMF, Harmonic Mitigation, Rotating Magnetic Field Transformer, Single-to-Three Phase Conversion.

## 1 Introduction

MOST of industrial electric consumers have been using electric energy in form of three phase system. For example, there may be required to use three phase induction motor on a single-phase supply where there is limited or no access to a three-phase network [1]. Although some optimizing methods can be implemented [2], a balanced three phase voltage is often required to ensure different load conditions with a desirable reliability. This example and many other related applications reveal the importance of single to three phase converters in recent decades [3-5]. Many literature discuss single to three phase conversion using power electronic elements. In [6, 7] two single-to-three-phase conversion systems are presented for a three-phase load application. The total harmonic distortion (THD) is improved using different power electronic switching elements as well as two inductors. A similar work with reduced number of switches is carried out in [8]. On the contrary, a six-leg single-to-three phase converter using numerous power electronic switching elements is introduced in [9]. The mentioned topology claimed to be suitable when load voltage's amplitude is half of the grid voltage as well as the load and grid voltage fundamental frequency should be the same. DC-link specification, voltage THD and other characteristics have been compared with conventional converter characteristics.

Single to three-phase converters can be embedded in other systems. A single-phase rectifier system for use with three phase drives has been introduced in [10]. Many issues are introduced and should be addressed such as higher ripple voltage across the DC bus capacitor, higher peak input current and THD. In single-to-three phase conversion, a large DC link capacitor is required which is fed by single-phase diode rectifier. Otherwise, the voltage ripple and then THD will be undesirably high. In [11] a control technique for an inverter inside the converter is proposed based on the

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power flow investigation between a DC link and a three-phase inverter which is led to low harmonic system. A similar converter in [12] with reduced number of switches is controlled using pulse width modulation (PWM) to drive three phase induction motor. In addition to the single-to-three phase conversion, a three-to-single phase conversion may also be considered to solve some problems like unbalance voltage, harmonics to the three-phase network. This type of phase conversion can be found in large power scales [13, 14]. In [15] another three-to-single phase conversion system is supposed to be used in electric vehicle charger.

Use of transformer structures together with converters may bring some advantages. Connection of the rectifier or inverter of a converter to the magnetic structure of the transformer and then hybridization can enable some advantageous specifications [16]. A transformer-based reduced components inverter is introduced in [17] for which the primary and secondary windings of a single-phase transformer are shared among the two bridges fed from a single DC supply. Generally, transformer-based converter topologies can also be found in different literature [18-20]. However, the transformer in these converters has no main role in the conversion strategy and just has a supplementary effect. A new type of transformer is introduced in [21] that directly influence the conversion technique in rectifier systems. The effectiveness of the proposed transformer in harmonic mitigation has been demonstrated. In [22], the proposed transformer is improved and redesigned for different types of rectifier systems.

In this paper, a new rotating magnetic field transformer is introduced in order to convert single-phase voltage to three-phase voltage. This transformer-based conversion technique just utilizes a few thyristor switches to establish orthogonal voltages creating a rotating magnetic field. As known, the conventional single to three phase is focused on the combination of rectifier and inverter while the main contribution of this paper is focused on the same conversion using round-shaped transformer. The proposed topology of the transformer improves the THD of the converter significantly.

## 2 Theory of Rotating-Magnetic-Field Transformers

Voltage induction in transformer windings are based on the magnetic field which is acting through them according to the Faraday's law. The induction is carried out in two ways. In the first method, windings are stationary and the pulsating magnetic field variations cause voltage induction. This is the same as the most of the transformers are working in such a principle. In power transformers, the magnetic field has a sinusoidal variation and then the induced voltage should be sinusoidal with different amplitude according to the turn ratio. There is a second way to induce voltage using rotating magnetic field in which the windings experience a magnetic field with different shifts of variation. In the rotating-magnetic-field transformers, the primary windings are due to produce such a rotating field. Hence, they are, despite of the conventional transformers, distributed windings. Based on the rotating field theory in AC electrical machines, there may be different possibilities to create it. The rotating filed can be created using a three-phase winding as in the induction and synchronous AC machines. In general, a $m$ phase system creates a rotating MMF as the following:

$$\Im(t,\theta) = m \times \frac{1}{2} \times F_m \cos(\omega t - \theta) \tag{1}$$

where $F_m$ is the amplitude of the MMF for each phase and $\omega$ is the angular frequency of the $m$ phase currents. A rotating magnetic field created with the smallest number of the phases can be reached by substituting $m = 2$. This is the case as we have in two phase induction machines.

Despite of the usual transformers in which there is no air gap linking the way of magnetic field from primary to the secondary windings, in rotating-filed transformers the magnetic flux passes through an air gap between them. Existence of air gap may have disadvantages in terms of high magnetizing current demand but passing magnetic flux through such an air gap will be beneficial from harmonics point of view [22]. A schematic of a two-phase winding is shown in Fig. 1 which is supplied from a two-phase current and hence leads to a rotating-magnetic-filed.

As shown in Fig. 1, there is 90° shift angle between phase windings. The same goes for the voltages and then currents suppling these windings.

When a rotating-magnetic-field is created, any other possible windings which are subjected to the field would experience an emf. These windings are the secondary windings of the transformer. The secondary voltage RMS of the rotating-magnetic-field transformers are dependent on the number of turns and

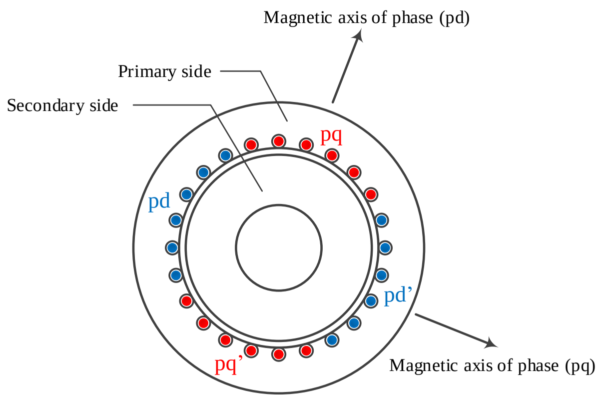



**Fig. 1** Schematic of a two-phase winding creating rotating-magnetic-filed.

winding distribution factor. There may be different phases in secondary side of the rotating-magnetic-filed transformers with desired shifts. Therefore, this type of transformers can be used as a phase converter so that it may convert a three-phases system to a two-phases system, three phase systems, five phases system… and also vice versa. All possible phase systems, independent on primary or secondary side of the transformer, must create a rotating-magnetic-field. Otherwise, there would be some problems in energy conversion in terms of current imbalance, low power factor under load conditions. Since three-phase system is always common, one of the primary or secondary side of the transformer will then be a three-phase winding. Single-phase winding cannot produce a rotating-magnetic-field and hence the conversion from/to single phase system seems to be impractical. The subsequent section explains how single to three phase conversion can be accomplished using a rotating-magnetic-field-transformer and a few switches.

## 3 Basic Concept, Modeling and Description of the Proposed Converter

As explained in the previous section, a rotating-magnetic-filed transformer can convert different phase systems to each other if all of which have the capability to create a rotating filed. However, single-phase system lacks to create such a filed. To convert single-phase to a three-phase system, at first it is supposed to convert a two-phase system to three-phase system using rotating-magnetic-field transformer and beside this, a new technique is introduced to attain a two-phase voltage from single-phase voltage using thyristor switches. It is necessary to clarify that the conversion is not actually based on the power electronic and the mentioned switches only work in low frequencies, for example 50 Hz, without any PWM. Therefore, the created two-phase voltage is not of ideal form and may has low quality in terms of THD. Nevertheless, during two to three-phase conversion using rotating-magnetic-filed transformer, the voltage quality is compensated. The compensation is reached using two sets of three-phase windings on the secondary which are individually supplying different loads. Because of 90° shift phase between the currents of two sets of windings and also a 90° mechanical shift angle between them, the resultant MMF in the air gap will be improved from harmonic point of view as explained in detail in [R22].

First, the rotating-magnetic-filed transformer is modeled. The primary side consists of two-phase winding which is going to be supplied from a single-phase system via thyristor switches. Each of primary windings located in the slots which have a shift angle of 90°. The voltage equation for the primary windings can then be written as the followings:

$$V_{pd} = r_{pd} i_{pd} + \frac{d\lambda_{pd}}{dt} \tag{2}$$

$$V_{pq} = r_{pq} i_{pq} + \frac{d\lambda_{pq}}{dt} \tag{3}$$

where $r_{pd}$ and $r_{pq}$ stand for the phase resistances, $i_{pd}$ and $i_{pq}$ denote the primary phase currents and, $\lambda_{pd}$ and $\lambda_{pq}$ are the phase flux linkages. There are two sets of three-phase windings on the secondary side. The shift angle between these sets is 90°. Similarly, the voltage equation for the secondary side is of the form:

$$V_{sn} = -r_{sn} i_{sn} + \frac{d\lambda_{sn}}{dt} \tag{4}$$

in which

$$(f_{sn})^T = [f_{sn1} \;\; f_{sn2} \;\; f_{sn3}] \tag{5}$$

and

$$V_{sm} = -r_{sm} i_{sm} + \frac{d\lambda_{sm}}{dt} \tag{6}$$

in which

$$(f_{sm})^T = [f_{sm1} \;\; f_{sm2} \;\; f_{sm3}] \tag{7}$$

In (4)-(7), $f_{sn}$ stand for the quantities which are related to the first set of three-phase windings on the secondary and $f_{sm}$ is for the second set of three-phase windings. Again, the indices "*n*" and "*m*" are used for the first and second sets of three phase winding in the secondary side while "*p*" is used for the primary side. In the proposed rotating-magnetic-filed transformer, the flux linkage equations become as follows:

$$\begin{bmatrix} \lambda_p \\ \lambda_{sn} \\ \lambda_{sm} \end{bmatrix}_{8\times1} = \begin{bmatrix} L_p & L_{psn} & L_{psm} \\ (L_{psn})^T & L_{sn} & L_{snsm} \\ (L_{psm})^T & (L_{snsm}) & L_{sm} \end{bmatrix}_{8\times8} \begin{bmatrix} i_p \\ i_{sn} \\ i_{sm} \end{bmatrix}_{8\times1} \tag{8}$$

where $\lambda_p$, $L_p$, and $i_p$ stand for flux linkages, inductances and currents of the primary two-phase winding respectively. It is convenient to transfer the secondary quantities to the primary side with appropriate ratios. Therefore, the transformed quantities will then be shown with prim notation. If turn numbers of the three-phase winding sets are not the same, different turn ratio must be used in transformation. Hence, the voltage equation matrix for the rotating-magnetic-filed transformer may be expressed as the following:

$$\begin{bmatrix} V_p \\ V'_{sn} \\ V'_{sm} \end{bmatrix}_{8\times1} = \begin{bmatrix} r_p + \rho L_p & \frac{2}{3}\rho L'_{psn} & \frac{2}{3}\rho L'_{psm} \\ \rho(L'_{psn})^T & r'_{sn} + \rho L'_{sn} & \rho L'_{snsm} \\ \rho(L'_{psm})^T & \rho(L'_{snsm}) & r'_{sm} + \rho L'_{sm} \end{bmatrix}_{8\times8} \begin{bmatrix} i_p \\ i'_{sn} \\ i'_{sm} \end{bmatrix}_{8\times1} \tag{9}$$

In (9), $\rho$ is the operator $d/dt$. Despite of the AC machines, there is no moving part in rotating magnetic-field transformers and then the inductances are constant and also there is no need to add a mechanical equation to the system. Nevertheless, using reference frame theory could help to derive magnetizing inductances simply. Considering reference frame in primary side and transferring the voltage and flux linkage equations lead to the followings:

$$V_{pd}^{p} = r_{pd} i_{pd}^{p} + \rho\lambda_{pd}^{p} \tag{10}$$
$$V_{pq}^{p} = r_{pq} i_{pq}^{p} + \rho\lambda_{pq}^{p} \tag{11}$$
$$V_{dsn}'^{p} = -r_{sn}' i_{dsn}'^{p} + \rho\lambda_{dsn}'^{p} - 0 \tag{12}$$
$$V_{qsn}'^{p} = -r_{sn}' i_{qsn}'^{p} + \rho\lambda_{qsn}'^{p} + 0 \tag{13}$$
$$V_{0sn}' = -r_{sn}' i_{0sn}' + \rho\lambda_{0sn}' \tag{14}$$
$$V_{dsm}'^{p} = -r_{sm}' i_{dsm}'^{p} + \rho\lambda_{dsm}'^{p} - 0 \tag{15}$$
$$V_{qsm}'^{p} = -r_{sm}' i_{qsm}'^{p} + \rho\lambda_{qsm}'^{p} + 0 \tag{16}$$
$$V_{0sm}' = -r_{sm}' i_{0sm}' + \rho\lambda_{0sm}' \tag{17}$$

The superscript "*p*" indicates stationary reference frame in the primary side. Equations (10) and (11) belong to the primary windings which are located on the *d* and *q* axis of the frame. Equations (12)-(14) and (15)-(17) belong to the first and second sets of the three-phase windings on the secondary side respectively. Additionally, the term "0" indicates that the there is no moving part and the reference frame is stationary as well and hence there will be no *motional emf*. In rotating-magnetic-filed transformer all we have is *transformer emf*. Similarly, using the mentioned reference frame results in the following expressions for the flux linkages:

$$\lambda_{pd}^{p} = -L_{lpd} i_{pd}^{p} + L_{md}(-i_{pd}^{p} + i_{dsn}'^{p} + i_{dsm}'^{p}) \tag{18}$$
$$\lambda_{pq}^{p} = -L_{lpq} i_{pq}^{p} + L_{mq}(-i_{pq}^{p} + i_{qsn}'^{p} + i_{qsm}'^{p}) \tag{19}$$
$$\lambda_{dsn}'^{p} = -L_{lsn}' i_{dsn}'^{p} + L_{md}(-i_{pd}^{p} + i_{dsn}'^{p} + i_{dsm}'^{p}) \tag{20}$$
$$\lambda_{qsn}'^{p} = -L_{lsn}' i_{qsn}'^{p} + L_{mq}(-i_{pq}^{p} + i_{qsn}'^{p} + i_{qsm}'^{p}) \tag{21}$$
$$\lambda_{0sn}' = -L_{lsn}' i_{0sn}' \tag{22}$$
$$\lambda_{dsm}'^{p} = -L_{lsm}' i_{dsm}'^{p} + L_{md}(-i_{pd}^{p} + i_{dsn}'^{p} + i_{dsm}'^{p}) \tag{23}$$
$$\lambda_{qsm}'^{p} = -L_{lsm}' i_{qsm}'^{p} + L_{mq}(-i_{pq}^{p} + i_{qsn}'^{p} + i_{qsm}'^{p}) \tag{24}$$
$$\lambda_{0sm}' = -L_{lsm}' i_{0sm}' \tag{25}$$

where $L_{lpd}$ and $L_{lpq}$ stand for leakage inductances of the primary windings, $L_{lsn}$ and $L_{lsm}$ is the leakage inductances for two sets of three-phase windings on the secondary side. also, $L_{md}$ and $L_{mq}$ are the magnetizing inductances in the *d* and *q* axis. The voltage equations (10)-(17) together with the flux linkage equations (18)-(25) determine state equations by which the proposed transformer's characteristic can be obtained.

Now, the proposed transformer must be supplied by a two-phase voltage ($V_{pd}$, $V_{pq}$). The strategy to obtain a two-phase voltage without any classic converter is to chop a voltage source according to Fig. 2. The firing angles $\alpha$ and $\beta$ are constants and may be adjusted to modify the phase and RMS of the chopped two-phase voltages. However, there is no necessity to redefine it and this remains as an additional option. Although the fundamentals have the same RMS and an electrical shift angle of 90° as a balanced two-phase system, the voltages still suffer from some harmonics. As explained before, rotating-magnetic-field transformer not only convert a two-phase system to a three-phase one but also it can mitigate harmonic contents by utilizing to sets of secondary three-phase windings which is located with a suitable angle (90°) from each other.

## 4 Design Methodology of the Proposed Converter

The proposed converter is illustrated in Fig. 3. The primary winding's circuit utilizes some thyristors to chop suitable voltages similar to a two-phase voltage. As shown, a set of reverse parallel thyristors is used to apply the chopped voltage, $V_{pd}$ in Fig. 2, to the primary winding '*pd*'. The thyristor firing angle, $\alpha$ in Fig. 2, is about $\pi/2$ radians and constant. Meanwhile, the firing angle of its reverse parallel thyristor will have $\pi$ radians shift. The thyristors need no commutation circuits and according to the voltage waveform in Fig. 2, they can be turned off naturally. On the other hand, the primary winding '*pq*' is supplied through reverse parallel thyristors with gate turn off capability. Considering the waveform of $V_{pq}$ in Fig. 2, the thyristor firing angle is about zero radian and it must be turned off after $\pi/2$ radians. Hence, line commutation cannot take place in this case and that is why gate turn off thyristors are chosen. It should be mentioned that the chopping circuit of the primary windings is not actually like an inverter because it is directly supplied from an AC source and working in low frequency (50 Hz) without any PWM methods. The generated voltages for the windings '*pd*' and '*pq*' are like two-phase voltages with some additional harmonics and will then be convert to an acceptable three-phase voltage by rotating-magnetic-field transformer.

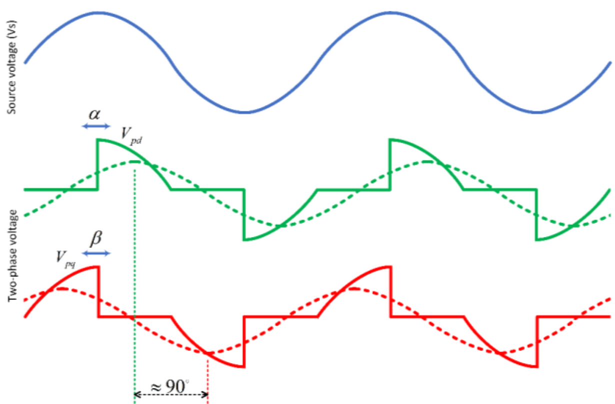



**Fig. 2** Deriving two-phase voltage by chopping a single-phase voltage source. Dashed lines refer to the fundamentals.

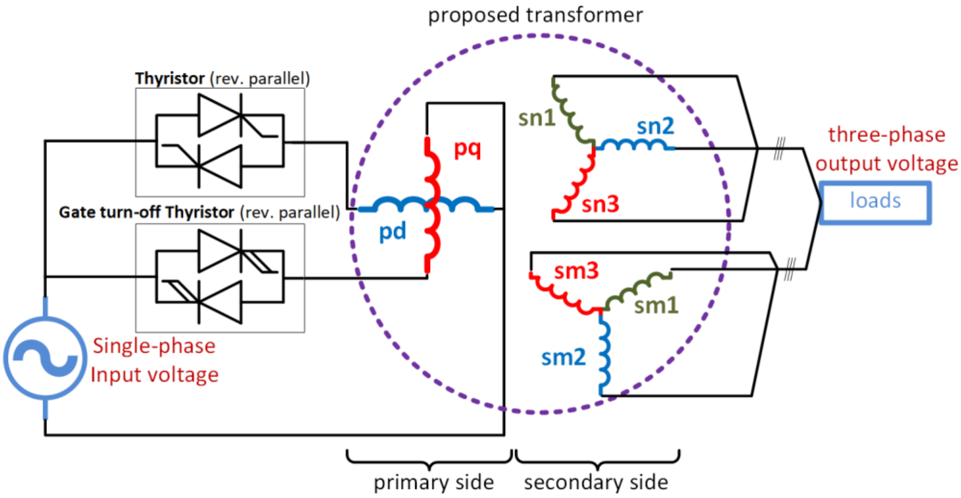



**Fig. 3** Block diagram of the proposed single-to-three phase converter using rotating-magnetic-filed transformer.

The phase angle of the voltage fundamental on the winding '*pd*' is 45.3° and on the winding '*pq*' is -44.8°. The RMS value of fundamental for both is the same. Therefore, the voltage fundamentals on the primary windings of the rotating filed transformer is about 90.1°. As a result, the primary fundamental voltages can create a rotating magnetic field by which a three-phase voltage will be induced on the secondary windings. However, there are some voltage harmonics which will cause corresponding magnetic rotating fields and as a result, the induced voltages on the secondary windings will contain the harmonics as well.

When the generated secondary three phases are used to supply load, the currents begin to flow in the secondary windings. According to the previous explanation, these currents may have different harmonics. Let us examine the effects of influential harmonics i.e. fifth and seventh harmonics. It should be mentioned that the third harmonic cannot be in the star connection. The constituted MMFs of the fifth harmonics are in the following forms:

$$\begin{aligned}\Im_{5sn} &= \kappa_m \cos 5\omega t \cos\theta \\ &+\kappa_m \cos 5(\omega t + 2\pi/3)\cos(\theta + 2\pi/3) \\ &+\kappa_m \cos 5(\omega t + 4\pi/3)\cos(\theta + 4\pi/3)\end{aligned} \tag{26}$$

in which $\Im_{5sn}$ is the fifth harmonic of the first set of secondary three-phase winding and $\kappa_m$ is a coefficient which is related to the winding distribution characteristics and load currents. For the second set of three-phase winding, the equation can be written as the following:

$$\begin{aligned}\Im_{5sm} &= \kappa_m \cos 5(\omega t + \pi/2)\cos(\theta + \pi/2) \\ &+\kappa_m \cos 5(\omega t + 7\pi/6)\cos(\theta + 7\pi/6) \\ &+\kappa_m \cos 5(\omega t + 11\pi/6)\cos(\theta + \pi/2 + 11\pi/6)\end{aligned} \tag{27}$$

If (27) is added to (26), the total MMF of the fifth harmonic will be zero:

$$\Im_5 = \Im_{5sn} + \Im_{5sm} = 0 \tag{28}$$

Besides, similar calculation can be carried out for the seventh harmonic. The total MMF of the seventh harmonic is also zero as the followings:

$$\begin{aligned}\Im_{7sn} &= \kappa_m \cos 7\omega t \cos\theta \\ &+\kappa_m \cos 7(\omega t + 2\pi/3)\cos(\theta + 2\pi/3) \\ &+\kappa_m \cos 7(\omega t + 4\pi/3)\cos(\theta + 4\pi/3)\end{aligned} \tag{29}$$

$$\begin{aligned}\Im_{5sm} &= \kappa_m \cos 7(\omega t + \pi/2)\cos(\theta + \pi/2) \\ &+\kappa_m \cos 7(\omega t + 7\pi/6)\cos(\theta + 7\pi/6) \\ &+\kappa_m \cos 7(\omega t + 11\pi/6)\cos(\theta + \pi/2 + 11\pi/6)\end{aligned} \tag{30}$$

$$\Im_7 = \Im_{7sn} + \Im_{7sm} = 0 \tag{31}$$

According to (28) and (31) there will be no demand for these MMFs in the primary windings and this in turn improve the total rotating magnetic field in the air gap. Other harmonics can be filtered and are of no importance.

The strategy to magnetic design of the proposed transformer is somewhat different in comparison to the AC machines and requires some special considerations. In order to ensure the thyristors performance, the primary windings should be designed in an accurate way in terms of inductances and also resistances. There must be compromises between the following equations aiming at high resistance to inductance ratio.

$$L_m = \pi\mu_0 N^2 r l_t / l_g \tag{32}$$

$$R_p = 2k_r k_{ac} N^2 r l_t \rho / S_s \tag{33}$$

$$V_p = 1.11 k_w N f\,(4\pi r l_t) B_{\max} \tag{34}$$

where $L_m$, $R_p$ and $V_p$ stand for magnetizing inductance, primary winding resistance and RMS value of the primary winding respectively. Additionally, $N$ is number of turns, $r$ and $l_t$ are the proposed transformer radius and length, $l_g$ is the airgap length. $k_r$ stands for end winding coefficient of primary windings, $k_{ac}$ for AC factor of the resistance, $\rho$ for electrical resistivity and $S_s$ for winding slot area. In (34), $k_w$ is the winding factor, $f$ is the supplied frequency and $B_{\max}$ is the maximum flux density. As can be seen, the $R_p/L_m$ ratio is independent of turn number. Therefore, increasement of this ratio has no direct impact on the RMS voltage in (34). According to the pervious equations, to reach a high value for $R_p/L_m$, an iron design with high magnetic loading is required which in turn lead to a low value for $S_s$. On the other side, high value of airgap length $l_g$ is desired to obtain a high $R_p/L_m$ ratio. However, increase of airgap length can lead to a large magnetizing current. Eventually, a compromise between design parameters is required to satisfactorily lead to a high resistance to inductance ratio which in turn ensure the thyristor performance.

According to the pervious explanation, in the proposed rotating magnetic field transformer a low value current in the primary and large current in the secondary is desired. Therefore, the operation capability will be increased if it is supposed to use the proposed transformer as a step-up transformer and plan a design procedure in such a way. It should be mentioned that if a gate turn-off thyristor is used instead for the winding ‘*pd*’ in Fig. 3, the design limitation for $L_m/R_p$ ratio will be of no importance. It should be mentioned that in the proposed converter system, the primary and secondary side of the round-shaped transformer are fixed and they are not allowed to move in any direction. Of course, the relative position of the secondary and primary side should be adjusted so that the inductance requirements are addressed as explained. In the no load condition, there will be zero torque on any part and since the secondary winding is connected to load circuit with some possible resistance, the produced torque will be negligible. In case short circuit is occurred in the secondary winding, which is not usual in the proposed system and regarded as fault, the torque will be appear. Therefore, torque production of the proposed system with round-shaped transformer is not a main concern.

## 5 Results and Comparison

In order to examine the proposed converter using rotating-magnetic-field transformer which is presented in previous sections in detail, the model of system is built to get simulation results. Beside the proposed model, to comparison, the simulation is also carried out for the conventional single-to-three phase converter. The proposed single to three phase conversion system is based on rotating magnetic field in round-shaped transformer and should be first compared with the conventional single to three phase conversion system. Moreover, there is no any other conversion system which is mainly based on a special transformer to compare. Again, in the proposed system, the mentioned transformer is as a main part of conversion not a part of it. The conventional single to three phase conversion system is a power electronic-based one. Therefore, it is unavoidable to compare the proposed system with this conventional sytem. To make the comparisons more reasonable, another technique is included in the conventional system. Fig. 4 illustrates the block diagram of the conventional converter for comparison purposes. As shown in Fig. 4, at first single phase voltage is rectified using diode full wave bridge and then the DC voltage is converted to three phase voltage using three phase full bridge inverter. To prevent harmonics and clarify the differences between the proposed and conventional converter, ripple of the input DC voltage for the inverter is mitigated using a large capacitor. Additionally, to make the comparison reasonable, a PWM technique is included in the conventional converter to improve the converter indexes. The main parameters associated with both converters are summarized in Table 1.

The conventional and proposed converter are examined with the same input voltage and the output conditions. Fig. 5 depicts one phase of the generated output three phase voltages for different converters. The proposed converter output voltage which is based on rotating magnetic field transformer is shown in Fig. 5(a). Besides, the generated output voltage for the conventional converter with square wave pulses is illustrated in Fig. 5(b). The simulation of conventional converter using SPWM technique is also carried out and the result is shown in Fig. 5(c). To get insight into the quality of voltages which are produced using different converters, harmonic contents of them are extracted and illustrated in Fig. 6. The THD of output voltage for the proposed converter possesses about 103% reduction in comparison to the conventional square wave converter and about 66% reduction in comparison to the conventional SPWM converter. The main harmonic of the output in the proposed converter is the third harmonic which is dependent on the secondary winding way of connection and may be further mitigated. As explained in previous section, the fifth and seventh harmonic in the proposed converter is significantly reduced compared with that of conventional converter because of rotating magnetic field transformer existence.

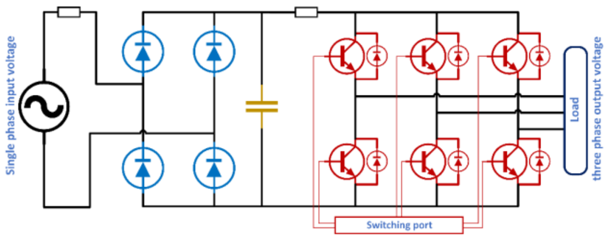



**Fig. 4** Block diagram of the conventional single-to-three phase converter.

**Table 1** main parameters of the single to three-phase converters.

| | | |
|---|---|---|
| **Electrical specifications** | | |
| Rated power, [hp] | | 16 |
| Rated frequency, [Hz] | | 50 |
| Input nominal voltage, [V] (RMS) | | 215 |
| Input nominal current, [A] (RMS) | | 70 |
| Output nominal voltage, [V] (RMS, L-L) | | 235 |
| Output nominal current, [A] (RMS, L-L) | | 25 |
| **Switching specifications** | | |
| | Conventional converter | Proposed converter |
| Number of power electronic components, transformers | 10 (4 diode, 6 IGBT), 0 | 4 (Thyristor), 1 |
| Switching frequency, [Hz] | >50 | 50 |
| DC link capacitor | Required | Not required |
| Electrical isolation of the output from input | Not isolated | Isolated |
| **Rotating magnetic field transformer specifications (in proposed converter)** | | |
| Primary winding nominal phase voltage, [V] | | 100 |
| Secondary winding nominal phase voltage, [V] | | 140 |
| Primary winding nominal phase current, [A] | | 35 |
| Secondary winding nominal phase current, [A] | | 25 |
| Turn ratio | | 7/5 |
| Transformer maximum losses, [%] | | 11 |

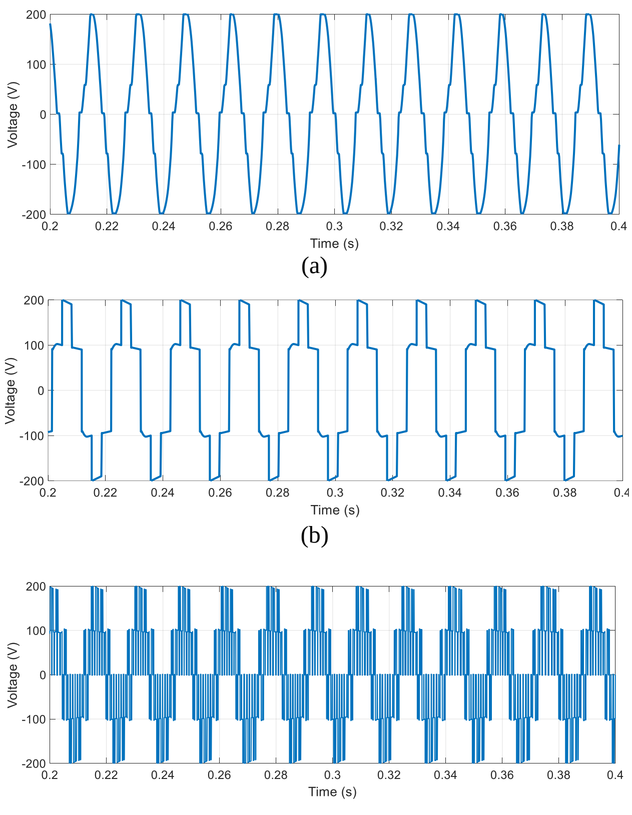



**Fig. 5** Output phase voltage in a) the proposed converter based on rotating magnetic field transformer, b), conventional converter with square wave modulation, and c) SPWM.

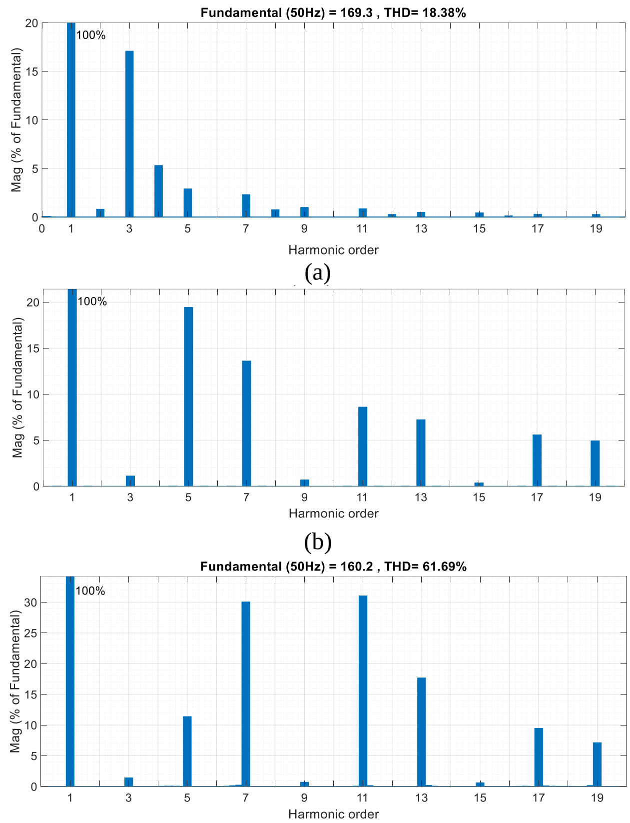
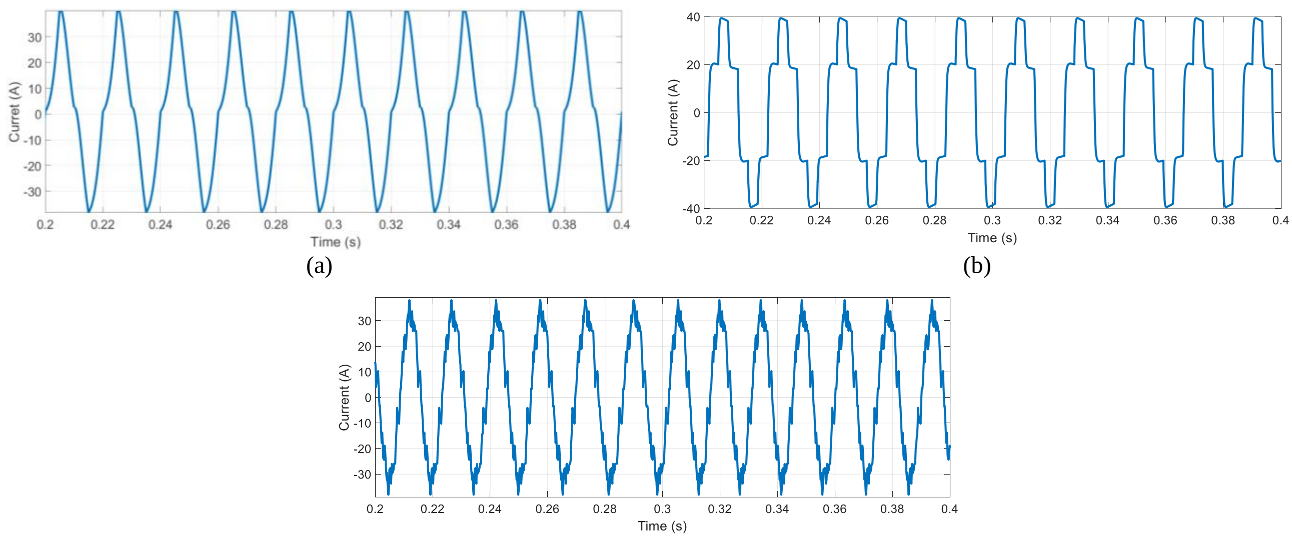



**Fig. 6** Harmonic contents of output phase voltage in a) the proposed converter based on rotating magnetic field transformer, b) conventional converter with square wave modulation, and c) SPWM.

For the nominal power, the output phase current waveforms are also extracted and shown in Fig. 7. The comparison is repeated for other load conditions and the results are summarized in Table 2. As explained in previous sections, the proposed rotating magnetic field transformer should be designed in such way that the resistance to inductance ratio remains in an acceptable range. The performance of the proposed system is further examined and compared for a RL load. The output current of the proposed and conventional converter with square wave modulation are shown in Fig. 8(a). The THD of output current for RL load is also extracted and shown in Fig 8(b). As predicted, the proposed converter delivers the current with low value of THD in comparison to the conventional one. That is because in the proposed converter, as explained before, low value of harmonics are induced in secondary side. Hence, low value of THD for voltage will appear in a similar way in the currents. The comparison is continued for the input currents as well. The input current waveforms of both conversion systems are depicted in Fig. 9. The proposed converter with rotating magnetic field transformer imposes less harmonics on the power source side. However, its RMS value is somewhat greater than the conventional system. That is because the transformer need more current for magnetizing which is caused by the air-gap. Fig. 10 depicts the voltage waveform switched via the thyristor supplying the winding ‘*pd*’ of the primary side in the rotating magnetic field transformer. As can be discoverable in this figure, the input voltage of the winding ‘pd’ may be deviated from what can be seen in Fig. 2. This deviation can be acceptable to some extent. However, for low value of the mentioned ratio there may be a necessity to use gate turn-off thyristor for supplying both of the primary windings. Also, as shown in Fig. 2, the firing angles $\alpha$ and $\beta$ can be influence the harmonic contents of the input voltages and then affect that of rotating magnetic field. This is further verified and the results are illustrated in Fig. 11. As can be seen, the angles between 88 to 94 degree lead to an MMF with minimum distortion.

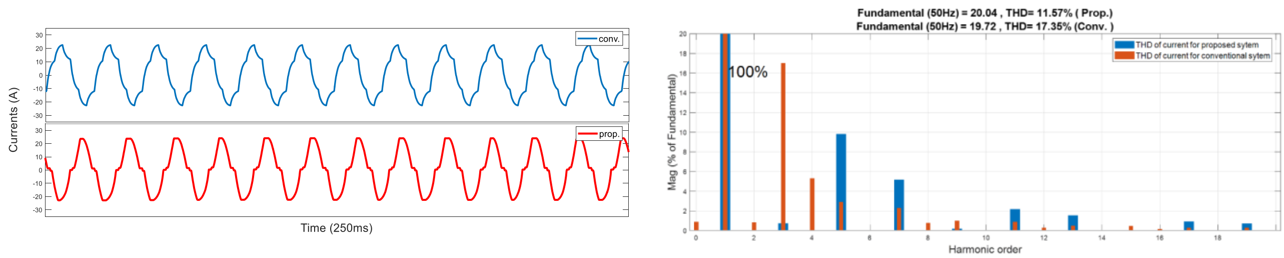



(a) (b) (c)

**Fig. 7** Output phase current in a) the proposed converter based on the rotating magnetic field transformer, b) conventional converter with square wave modulation, and c) SPWM.

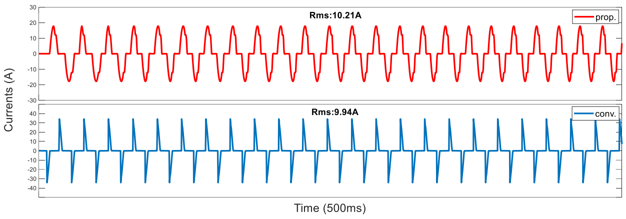
**Table 2** Harmonic comparisons of the proposed and conventional converters for different loads.

| Load [%] | Total harmonic distortion (THD) [%] | | |
|---|---|---|---|
| | proposed converter | conventional converter (Square Wave Modulation) | conventional converter (SPWM) |
| 100 | 18.1 | 103.3 | 66.4 |
| 50 | 14.0 | 89.2 | 54.8 |
| 25 | 13.3 | 81.6 | 52.4 |

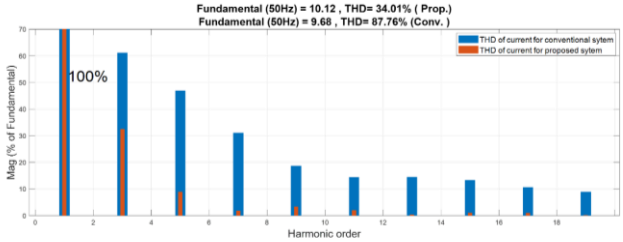



(a) (b)

**Fig. 8** a) Output current waveforms of the proposed and conventional (square wave modulation) converter systems and b) harmonic contents (THD) of the currents.




(a)




(b)

**Fig. 9** a) Input current waveforms of the proposed and conventional (square wave modulation) converter systems and (b) harmonic contents (THD) of the currents.

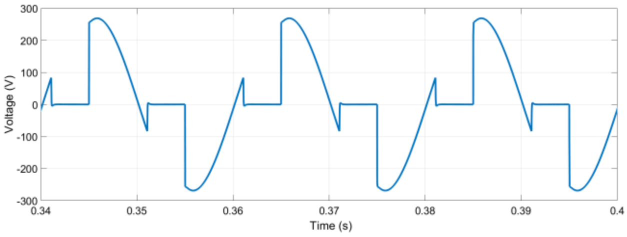



**Fig. 10** Voltage waveform on the winding '*pd*' of the proposed transformer.

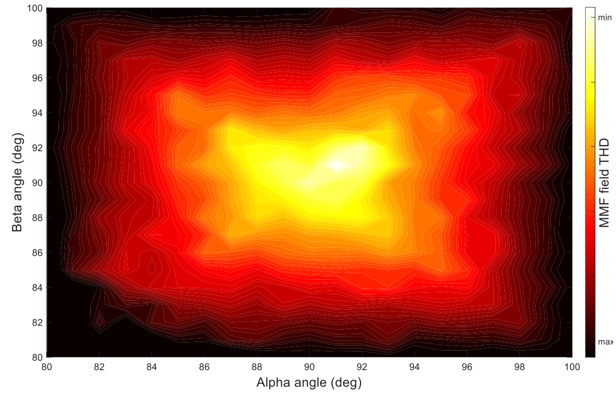



**Fig. 11** THD distortion of the resultant MMF in terms of firing angles $\alpha$ and $\beta$.

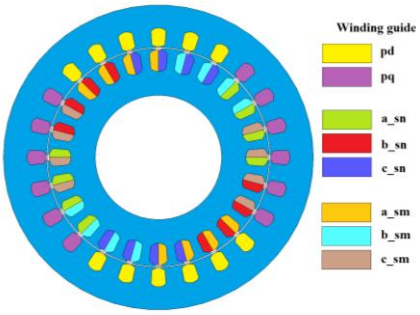
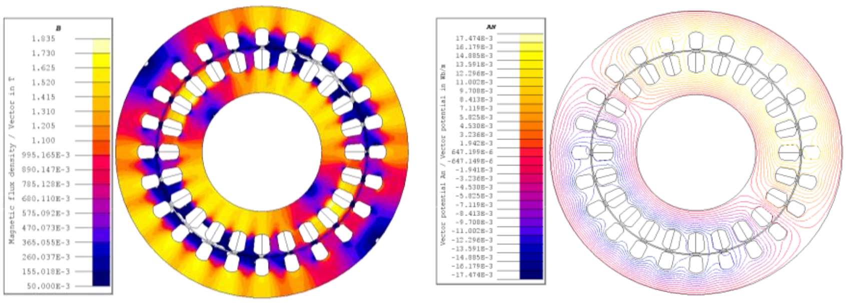



**Fig. 12** Schematic of the proposed round-shaped transformer and its winding arrangements.



(a) (b)

**Fig. 13** a) magnetic flux density and b) flux lines of the round-shaped transformer in the proposed system.

Finally, in order to verify the analysis mentioned in the paper using reference frame theory, the round-shaped transformer is also modeled using FEM. First, the main dimensions of a typical 16hp induction motor are initially considered for the round-shaped transformer. Then, the air gap length, slot designs, winding arrangement and distribution are modified based on the round-shaped transformer concepts. Fig. 12 shows geometrically a schematic of the round-shaped transformer and also its different winding arrangements. The round-shaped transformer in the proposed converter system is analyzed using FEM simulation. Fig. 13 depicts the magnetic field and flux lines of the proposed round-shaped transformer. As shown, the transformer has 24 slots in the primary and secondary side and windings distribution creates two poles. There may be some different topologies with different slots and winding arrangements but the main principle is the same as mentioned in previous sections. Moreover, using a high number of slots per winding is always beneficial because the MMF distribution would be better and this makes good agreement between the analytical and FEM results. However, the number of slots is limited.

The output voltage of the proposed converter system is calculated using FEM simulation and compared with the results of analytical equations. Fig. 14 depicts this comparison in terms of output voltage. As shown, there is a good agreement between them and FEM results exhibit more content of harmonics. That is because in

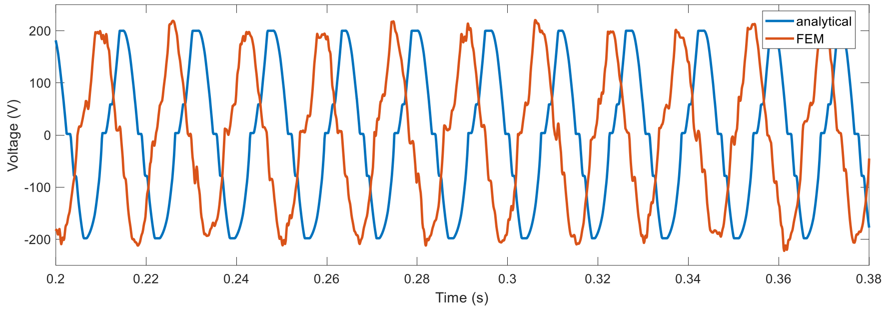



**Fig. 14** The output voltage waveforms of the proposed system using FEM and analytical results.

FEM simulation the windings are not distributed ideally. The calculated THD for FEM analysis is 7 percent higher in comparison to the analytical solution. However, this difference is negligible and can be ignored considering the comparison results with conventional converter system. It should be mentioned that in the proposed round-shaped transformer the relative position of the primary and secondary core is of no importance from winding point of view. Because it may only affect the shift phase of voltage on the secondary. However, relative position from tooth-tooth to tooth-slot position influences the winding inductance. To reduce magnetizing current the first relative position is chosen.

## 6 Conclusions

This paper proposes a new single-to-three phase converter which is based on a special type of rotating magnetic field transformers. In the mentioned transformer, as its name implies, a rotating magnetic field must be established first, hence a switching technique is introduced to obtain nearly a two-phase voltage. In the proposed switching technique, a minimum number of switching components are intentionally used and the created two-phase voltage should then have some harmonics. In the second step, the transformer winding arrangement are modified to remove the effects of these harmonics in the output. Some design consideration and limitation are also included. To obtain results, the proposed transformer is modeled and the system is simulated for different load conditions. The results confirm the validity of the proposed converter. Also, the output voltage distortion of the proposed converter is reduced compared to the conventional single-to-three phase converter. However, resistance to inductance ratio should be designed with care for the proposed transformer. FEM modeling is also included and compared with the analytical calculation. In the proposed converter, the input and output are electrically isolated and the proposed converter may be a good candidate where it is required to have a minimum number of power electronic-based components for conversion.

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