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Simulation of Special Connection Scheme of Multi winding Transformers for Three to Five Phase Power Transformation

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Abstract: Multiphase (>3Ø) systems are greatly under research recently due to their inherent advantages compared to their three-phase (3Ø) counterparts. The Multiphase system applicability is explored in electric power generation, transmission, and utilization. The first multiphase motor drive proposal was given by Ward and Harrer way back in 1969.The grid supply is available as three phase supply, hence there is a static phase transformation system required to obtain a multiphase supply from the available three-phase supply. Multiphase Inverters and Special Transformer connection Technique are two methods used to convert Three-phase supply to Five-phase supply. In this paper three to five phase transformation using special multi-winding transformer connection scheme is presented. Three single phase Multiwinding transformers are designed, two transformers having one primary and three secondary windings and the third transformer has one primary and two secondary windings. The proposed transformer connection has three phase input and outputs five phases to transform balanced fixed voltage-fixed frequency three phase power into balanced fixed voltage-fixed frequency five phase power at its output. The special connection scheme of multi-winding transformers is simulated by using 'SIMPOWERSYSTEMS' block sets of MATLAB/SIMULINK software.

Keywords: five phase (5Ø), multiphase, three phase (3Ø), transformer, Turn ratio, Higher Phase Order (HPO).

I. INTRODUCTION

Power system with more than three phases is called Multiphase power system. Multiphase systems are being focused on for research due to their inherent advantages compared to 3Ø systems. The multiphase systems applicability is explored in electric power generation, transmission, and utilization. The 3Øconcepts can be used to construct and analyze various performance characteristics and voltage stability of the multi-phase line [1].The research on six-phase transmission system started to tackle the rising cost of right of way for transmission corridors, environmental issues, and stringent licensing laws. The multi-phase lines (6Ø and 12Ø) show progressively higher power handling capacity, low reactive power losses, higher receiving end power, and require low reactive power to maintain stable load voltage, which further reduces rating of compensating devices, and improves voltage stability in case of voltage dependent load and also increases line load ability in uncompensated as well as compensated condition. [1]. Theses aspects of multi-phase lines are very attractive and benefit the electric transmission utility. A 6Ø and 12Ø system is found to produce less ripple with a increased ripple frequency in an ac–dc rectifier system [1]. For multipulse rectifier system 6Øand 12Øtransformers are designed. The reason to choose a 6Ø, 12Ø, or 24Ø system is that they are multiples of three and their design is simple and straightforward.

Multiphase variable speed drives date back to the late 1960s, when ac drives fed from inverter were in the initial development stage. Low frequency torque ripple was one particular problem faced due to the six step mode of 3Ø inverter operation. The lowest frequency of torque ripple harmonic in an n-phase machine depends on time harmonics of the supply of the order $2n \pm 1$ (its frequency is 2n times higher than the supply frequency), therefore increasing the number of phases of the machine appears as the best solution to the problem. Increasing the number of phases will also improve the reliability since the drive can start and run even after the failure of one of the phases. Employing higher number of phases increases frequency of torque pulsations in the drive while lowering its amplitude. This will ensure satisfactory performance of the inverter-fed motor even at lower speeds. It has also been established that the Higher Phase Order motors have better electrical efficiency compared to that of a 3Ø motor **[3].** This has resulted in a substantial increase in the interest for multi-phase/Higher phase order drive systems worldwide [2]. Significant efforts have been put into the development of 5Ø and 6Ø variable-speed drives supplied from both voltage source and current source inverters due to their multiple advantages [4]–[5].Although the concept of variable-speed drives, based on utilization of multiphase (n >3) machines, was initiated in late 1960s, it was not until the mid- to late 1990s that multiphase drives came to be considered as serious contenders for various applications that include electric ship propulsion, locomotive traction, electric and hybrid electric vehicles, "more-electric" aircraft, and high-power industrial applications.

In a balanced 5Ø induction motor, the five stator phases are distributed with a spacing of **72 degrees.** The squirrel cage rotor similar to that used in a three-phase motor is used. When the stator phase coils are excited by balanced 5Ø-sinusoidal supply a rotating magneto-motive force (MMF) of constant amplitude is produced in the air gap. The rotating magnetic field causes rotor reaction and produces useful torque that drives the rotor. The 5Ø Induction motors are largely supplied from voltage/current source inverters [5][7].

This paper is organized in the following manner in Section I Introduction, Section II Three phase to five phase transformation techniques, Section III Transformer Winding arrangement for three phase to five phase transformation, Section IV Voltage Equations, Section V Simulation Results, and Section VI concludes the paper.

II. 3Ø TO 5Ø TRANSFORMATION TECHNIQUES

3Ø supply can be transformed into five phase supply by using following methods:

1. Using ac/dc/ac converters (Multiphase Inverter)
2. Using Multi winding transformer with special connection scheme

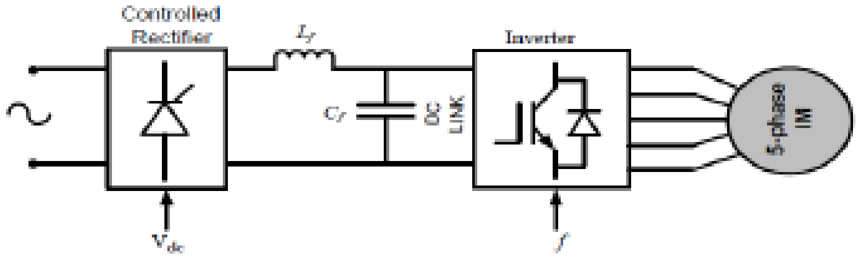

Figure 1-Five phase Inverter fed Induction motor

Fig. 1 shows a 5-leg inverter feeding a 5Ø Induction motor drive. There are time harmonic componentsin the output voltage of the inverter injecting harmonic currents into stator winding coils of the motor. The 5Øconnection eliminates the 5th and other quintuple-order harmonics, but the other harmonics having varying amplitudes and phase sequences will be present. Although the supply obtained from a 5-leg inverter may have more current ripple, there are control methods that can be used to lower the distortion in current to even below 1%, depending on the requirement and application where the 5Ø motor is used

.

The designed motor needs to be tested under a number of operating conditions with a pure sinusoidal supply to ensure its desired performance [6]. A No-load test, Blocked rotor test, and load tests are generally performed to determine the parameters of the motor. The machine parameters obtained by using the pulse width-modulated (PWM) supply may not provide the precise true value, hence a pure sinusoidal supply is required to feed the motor.

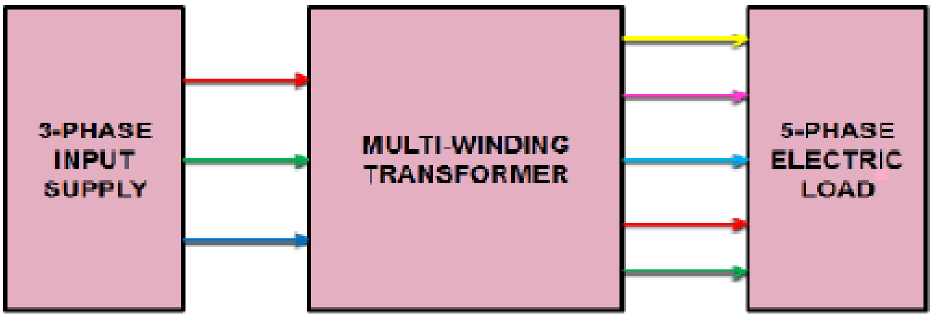

Figure 2-Block diagram of the proposed system

A special multi-winding transformer connection scheme to transform 3Ø to 5Ø supply is presented in this paper. The block diagram of the transformation system proposed is shown in Fig. 2 which can transform fixed voltage-fixed frequency 3Øgrid supply into the fixed voltage-fixed frequency 5Ø supply at its output. Variable output voltage may be obtained by connecting a 3Øautotransformer at the input side.

III. TRANSFORMER WINDING CONNECTION FOR THREE TO FIVE PHASE TRANSFORMATION

Three single phase Multiwinding transformers are designed with each having one primary and three secondary windings, except in one transformer where only two secondary windings are used. Fig. 3 shows transformer winding arrangement for 3Ø to 5Øtransformation. Primary winding of each transformer may be connected in Star or Delta across the 3Ø grid supply. The 16 terminals of secondary windings can be connected in different ways resulting in 5Ø-star or 5Ø-polygon output. Therefore we can have Input star-output star; Input star-output polygon; Input delta-output star; or Input delta-output polygon type of supply arrangements. The requisite phase angle of $360/_5 = 72^{\circ}$ between the output phases is obtained using appropriate turn ratios. The governing phasor equations are illustrated in section IV. Each phase has a different turn's ratio that is calculated from voltage equations. The choice of turn ratio is the main key factor to create the required phase displacement. Turn ratios required to obtain 5Ø Star output are presented in Table-I.

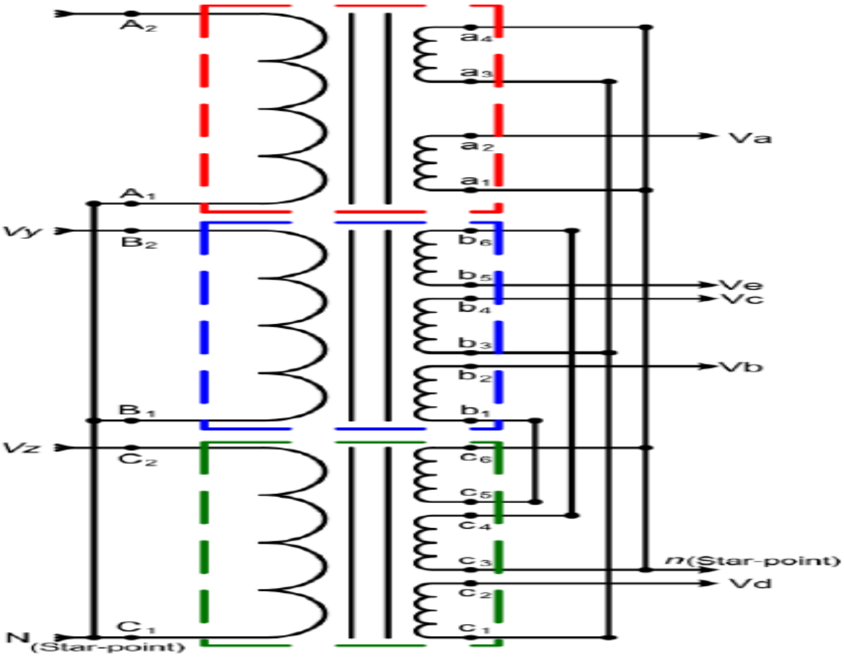

Figure 3-Transformer Winding arrangement

Letters "X" "Y", and "Z" denote input phases and letters "a", "b", "c", "d", and "e" are used to designate the five output phases. Fig. 4(a) shows connection diagram to connect secondary windings of each multi-winding transformer to obtain 5Ø-Star output. Phasor diagram shown inFig.4 (b), illustrates that voltage in first output phase "a" is equal and along that in input phase "X". The voltage in second output phase "b" is obtained from the phasor sum of voltages induced in windings "b_1b_2" and "c_6c_5", the third output phase "C" is obtained by the phasor addition of voltages induced in windings "b_3b_4" and "a_4a_3" and voltage in fourth output phase "d" is obtained by the phasor sum of voltages induced in windings"c_1c_2" and"a_4a_3" and similarly voltage in fifth output phase "e" is the result of phasor addition of the voltages induced in windings"b_6b_5 " and" c_3c_4".

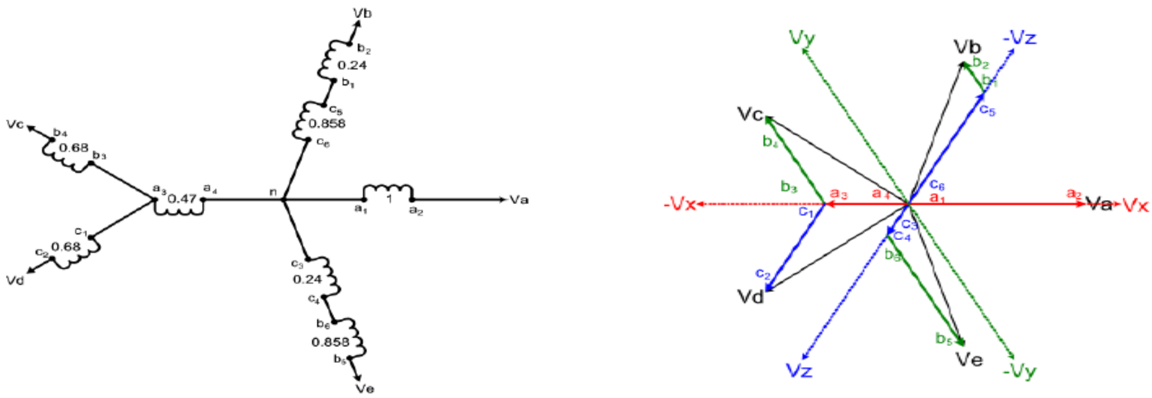

Figure 4-(a)-Connection of Secondary Windings to obtain Five phase Star output; (b) Phasor Diagram

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IV. VOLTAGE EQUATIONS

From the phasor diagram the equations for output phase voltage in terms of input phase voltages are given as follows:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} = \frac{1}{Sin(\frac{\pi}{3})} \begin{bmatrix} Sin(\frac{\pi}{3}) & 0 & 0 \\ 0 & Sin(\frac{\pi}{15}) & -Sin(\frac{4\pi}{15}) \\ -Sin(\frac{2\pi}{15}) & Sin(\frac{\pi}{5}) & 0 \\ -Sin(\frac{2\pi}{15}) & 0 & Sin(\frac{\pi}{5}) \\ 0 & -Sin(\frac{4\pi}{15}) & Sin(\frac{\pi}{15}) \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} \quad (1)$$

If $V_a = V_{max}\, Sin\, \omega t$ is reference voltage then instantaneous voltages of other five phases with respect to the reference voltage are given by equations (2) to (9) given below.

$$V_a = V_{max}\, Sin\, \omega t \quad (2)$$

$$V_b = V_{max}\, Sin\left(\omega t + \frac{2\pi}{5}\right) \quad (3)$$

$$V_c = V_{max}\, Sin\left(\omega t + \frac{4\pi}{5}\right) \quad (4)$$

$$V_d = V_{max}\, Sin\left(\omega t - \frac{4\pi}{5}\right) \quad (5)$$

$$V_e = V_{max}\, Sin\left(\omega t - \frac{2\pi}{5}\right) \quad (6)$$

$$V_x = V_{max}\, Sin\, \omega t \quad (7)$$

$$V_y = V_{max}\, Sin\left(\omega t + \frac{2\pi}{3}\right) \quad (8)$$

$$V_z = V_{max}\, Sin\left(\omega t - \frac{2\pi}{3}\right) \quad (9)$$

Equation (1) gives three phase to five phase transformation. Five phase to three phase transformation can be obtained by inverting (1). The same is given by equation (10).

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \frac{1}{Sin\,(\frac{\pi}{3})} \begin{bmatrix} Sin(\frac{2\pi}{5}) & 0 & 0 & 0 & 0 \\ 0 & Sin(\frac{2\pi}{15}) & Sin(\frac{4\pi}{15}) & 0 & 0 \\ 0 & 0 & 0 & Sin(\frac{4\pi}{15}) & Sin(\frac{2\pi}{15}) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} \quad (10)$$

Table I-Turn Ratio to obtain 5Ø- Star output

Phase	Secondary winding	Secondary to primary Turns ratio
X	$a_1 a_2$	1
	$a_4 a_3$	0.47
Y	$b_1 b_2$	0.680
	$b_4 b_3$	0.858
	$b_5 b_6$	0.24
Z	$c_1 c_2$	0.68
	$c_4 c_3$	0.24
	$c_5 c_6$	0.858

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V. SIMULATION RESULTS

The multi-winding transformer connection scheme is simulated by using "sim power system" block sets of the Matlab/Simulink software. The model is constructed using inbuilt multi-winding transformer blocks to simulate the conceptual design. The simulation is run by setting appropriate turn ratios (shown in Table-I) in the dialog box.

The simulation model for star connection on input side and star connection on output side is depicted in Fig. 5. Fig. 6 (a) and (b) shows Input and output voltage waveforms and the corresponding Input and output current waveforms are shown by Fig. 9(a) and (b). It can be concluded that for a balanced 3Ø input supply the output is a balanced 5Ø supply

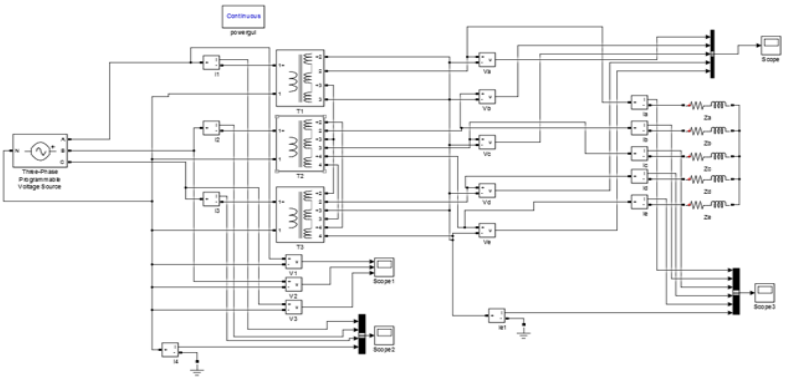

Figure 5-Simulink model for Input three phase Star and Output five phase Star

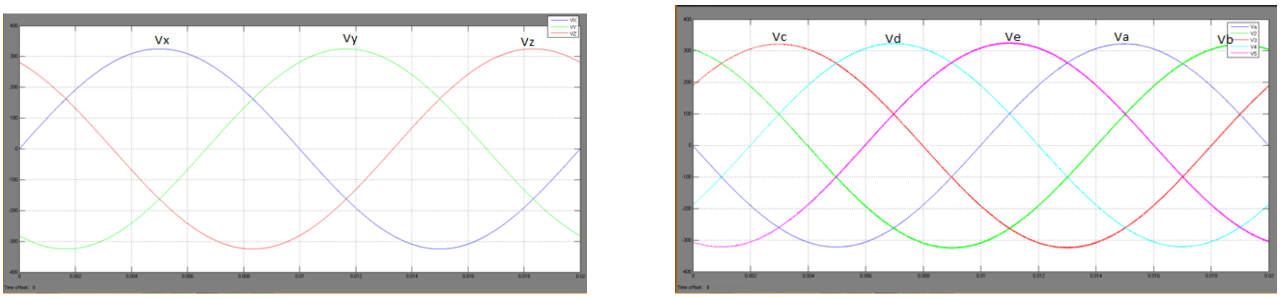

Figure 6-(a) Input Voltages Va=Vb=Vc=325(pk-pk); (b)-Output Voltages Va=Vb=Vc=Vd=Ve=325V(pk-pk)

Individual output phase Voltage waveforms are, shown in Figure 7 (a), 7(b), 8(a), and 8 (b) along with their respective input voltages. The phase voltage Va is along and equal to input phase voltage Vx, hence is not shown.

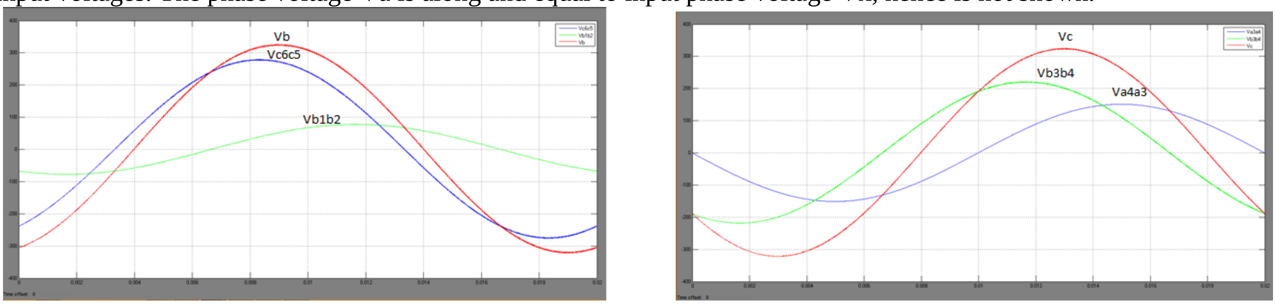

Figure 7- (a)-Vb=0.24 Vy (Vb1b2)-0.858 Vz(Vc5c6); (b) -Vc=0.68Vy(Vb3b4)-0.47Vx(Va3a4)

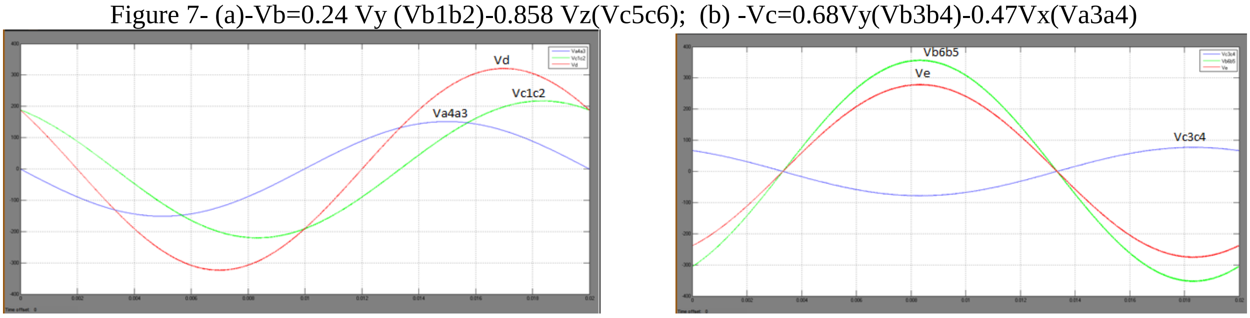

Figure 8-Vd=0.68Vz(Vc1c2)-0.47Vx(a4a3); (b) -Ve=0.24Vz(Vc3c4)-0.858Vy(Vb5b6)

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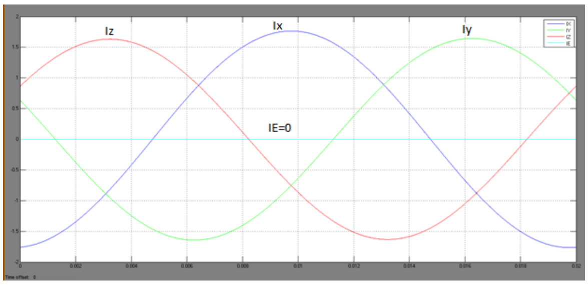

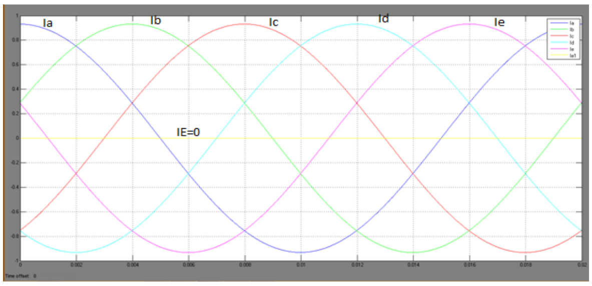

Figure 9-(a)-Three Phase Input currents; (b)-Five Phase Output Currents

No earth current was flowing when neutrals on both sides were earthed. The current waveforms in Figure 9(a) and 9(b) illustrate that the current flowing in transformer, connected to the input phase ‘X’, is higher than current flowing in the transformers connected across the other two phases at the input. This lowers the electrical efficiency of the overall transformer set.

VI. CONCLUSION

This paper has presented a special multi-winding transformer connection scheme to transform the constant frequency-constant voltage 3Ø power supply from grid to constant frequency-constant voltage 5Ø power supply at the output. The connection diagram and the phasor diagram, turn ratios along with governing voltage equations are illustrated. Viability of the transformation system is proved by connecting R-L load across the 5Ø supply obtained from proposed transformation system. The transformation scheme proposed can be used in drive applications and may also be further explored to be used in multiphase power transmission systems.

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