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Fork-Connected Autotransformer Based 30-Pulse AC-DC Converter for Power Quality Improvement

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Abstract: This paper presents the design and analysis of a novel fork-connected autotransformer based 30-phase ac-dc converter which supplies direct torque controlled induction motor drives (DTCIMD's) in order to have better power quality conditions at the point of common coupling. The proposed converter output voltage is accomplished via five paralleled 6-pulse ac-dc converters each of them consisting of 3-phase diode bridge rectifier. An autotransformer is designed to supply the rectifiers. The proposed converter requires five inter-phase transformers in the dc link. The design procedure of magnetics is in a way such that makes it suitable for retrofit applications where a six-pulse diode bridge rectifier is being utilized. The aforementioned structure improves power quality criteria at ac mains and makes them consistent with the IEEE-519 standard requirements for varying loads. Furthermore, near unity power factor is obtained for a wide range of DTCIMD operation. A comparison is made between 6-pulse and proposed converters from view point of power quality indices. Results show that input current total harmonic distortion (THD) is less than 2% for the proposed topology at variable loads.

Index Terms: AC–DC converter, fork-connected autotransformer, power quality, 30 pulse rectifier, direct torque controlled induction motor drive (DTCIMD).

1. Introduction

Recent advances in solid state conversion technology has led to the proliferation of variable frequency induction motor drives (VFIMD's) that are used in several applications such as air conditioning, blowers, fans, pumps for waste water treatment plants, textile mills, rolling mills etc [1].

The most practical technique in VFIMD's is direct torquecontrolled strategy in that it offers better performance rather than the other control techniques. direct torquecontrolled technique is implemented in voltage source inverter which is mostly fed from six-pulse diode bridge rectifier, Insulated gate bipolar transistors (IGBT's) are employed as the VSI switches.

The most important drawback of the six-pulse diode-bridge rectifier is its poor power factor injection of current harmonics into ac mains.The circulation of current harmonics into the source impedance yields in harmonic polluted voltages at the point of common coupling (PCC) and consequently resulting in undesired supply voltage conditions for costumers in the vicinity.The value of current harmonic components which are injected into the grid by nonlinear loads such as DTCIMD's should be confined within the standard limitations. The most prominent standards in this field are IEEE standard 519 [2] and the International Electrotechnical Commission (IEC) 61000-3-2 [3].

According to considerable growth of Static Power Converters (SPC's) that are the major sources of harmonicdistortion and as a result their power quality problems, researchers have

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ocused their attention on harmonic eliminating solutions. For DTCIMD's one effective solution is to employ multipulse AC-DC converters. These converters are based on either phase multiplication or phase shifting or pulse doubling or a combination [4]-[21].Although, in the conditions of light load or small source impedance, line current total harmonic distortion (THD) will be more than 5% for up to 18-pulse AC-DC converters.

A Polygon-Connected Autotransformer-Based 24-pulse AC-DC converter is reported in [17] which has THD variation of 4.48% to 5.65% from full-load to light-load (20% of full-load). Another T-Connected Autotransformer-Based 24-Pulse AC–DC Converter has also been presented in [18], however, the THD of the supply current with this topology is reported to vary from 2.46% to 5.20% which is more than 5% when operating at light load. However, some applications need strict power quality specifications and therefore the usage of converters with pulses more than 24 is unavoidable.

The 36-pulse was designed for VCIMD's in [21] which has THD variation of 2.03% to 3.74% from full-load to light-load (20% of full-load) respectively. The 40-pulse topology [22] was designed for VCIMD's loads having a THD variation of 2.23% to 3.85% from full-load to light-load (20% of full-load) respectively which is more than 3% when operating at light load, and the dc link voltage is higher than that of a 6-pulse diode bridge rectifier, thus making the scheme nonapplicable for retrofit applications.

The proposed design method will be suitable even when the transformer output voltages vary while keeping its 30-pulse operation. In the proposed structure, five 3-leg diode-bridge rectifiers are paralleled via five interphase transformers and fed from an autotransformer. Hence, a 30-pulse output voltage is obtained. Detailed design tips of the IPT and totally the whole structure of 30-pulse ac-dc converter are described in this paper and the proposed converter is modeled and simulated in MATLAB to study its behavior and specifically to analyze the power quality indices at ac mains. Furthermore, a 30-pulse ac-dc converter consisting of a fork-connectedautotransformer, five 6-pulse diode bridge rectifiers paralleled through five IPTs, and with a DTCIMD load Figure 1.

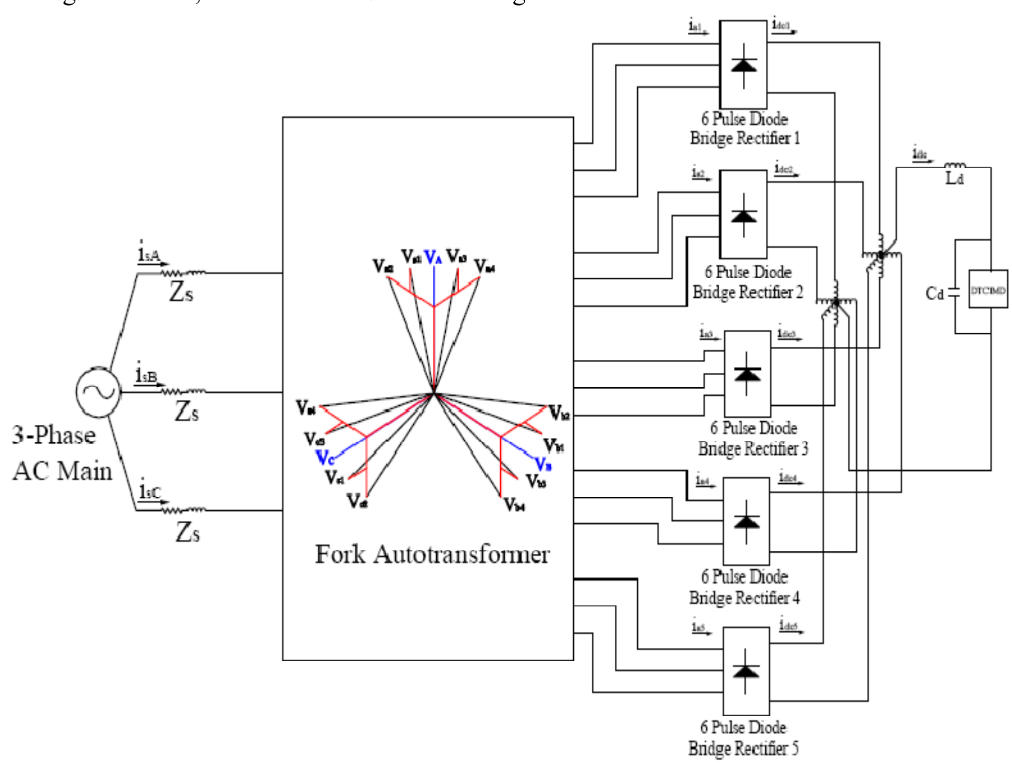

Figure 1. Fork-connected autotransformer configuration for 30-pulse ac–dc conversion.

Simulation results of six-pulse and proposed 30-pulse ac-dc converters feeding a DTCIMD load are scheduled and various quality criteria such as THD of ac mains current, power factor, displacement factor, distortion factor, and THD of the supply voltage at PCC are compared.

2. Proposed 30-Pulse AC–DC Converter

In order to implement a 30-pulse ac-dc converter through paralleling five bridge rectifiers, i.e. five 6-pulse rectifiers, five sets of three-phase voltages with a phase difference of 120 degrees between the voltages of each group and 12 degrees between the same voltages of the five groups are required. Accordingly, each bridge rectifier consists of 3 common-anode and 3 common-cathode diodes (five 3-leg rectifiers). Autotransformer connections and its phasor diagram which shows the angular displacement of voltages are illustrated in Figure 2.

A. Design of Proposed Autotransformer for 30-Pulse AC–DC Converter

The aforementioned five voltage sets are called as (V_{a1}, V_{b1}, V_{c1}) and (V_{a2}, V_{b2}, V_{c2}) and (V_a, V_b, V_c) and (V_{a3}, V_{b3}, V_{c3}) and (V_{a4}, V_{b4}, V_{c4}) that are fed to rectifiers I, II, III, IV and V, respectively. The same voltages of the five groups, i.e. V_{ai}, are phase displaced of 12 degrees. V_{a1} and V_{a3} has a phase shift of +12 and -12 degrees from the input voltage of phase A, respectively. According to phasor diagram, the 3-phase voltages are made from ac main phase and line voltages with fractions of the primary winding turns which are expressed with the following relationships.

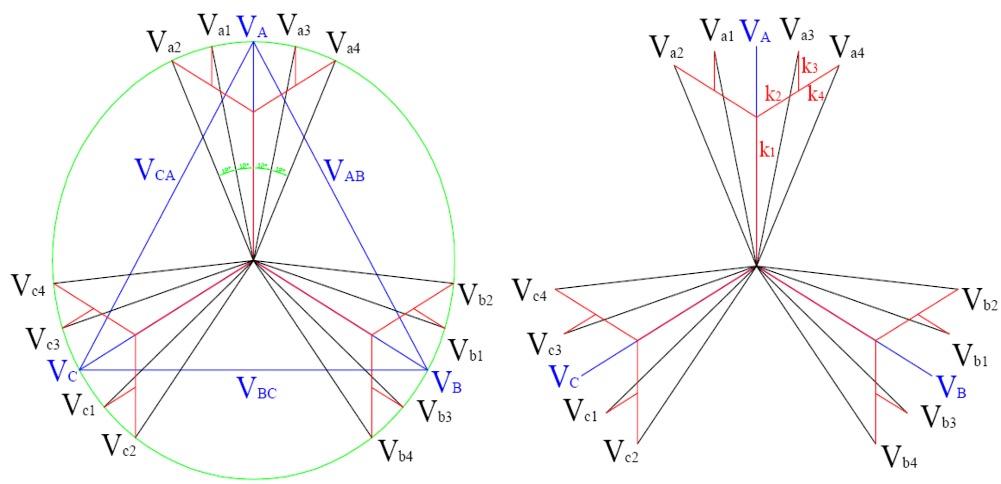

Figure 2. Fork connection of proposed autotransformer for 30-pulse converter and its phasor representation.

Assume the following set of voltages:

$$V_A = V_s\angle 0^\circ,\ V_B = V_s\angle -120^\circ,\ V_C = V_s\angle 120^\circ. \tag{1}$$

$$V_{a1} = V_s\angle 12^\circ, V_{b1} = V_s\angle -108^\circ, V_{c1} = V_s\angle 132^\circ, \tag{2}$$

$$V_{a2} = V_s\angle 24^\circ, V_{b2} = V_s\angle -96^\circ, V_{c2} = V_s\angle 144^\circ, \tag{3}$$

$$V_{a3} = V_s\angle -12^\circ, V_{b3} = V_s\angle -132^\circ, V_{c3} = V_s\angle 108^\circ, \tag{4}$$

$$V_{a4} = V_s\angle -24^\circ, V_{b4} = V_s\angle -144^\circ, V_{c4} = V_s\angle 96^\circ, \tag{5}$$

Input voltages for converter I are:

$$V_{a1} = K_1 V_A - K_2 V_B + K_3 V_A$$
$$V_{b1} = K_1 V_B - K_2 V_C + K_3 V_B$$
$$V_{c1} = K_1 V_C - K_2 V_A + K_3 V_C \quad (6)$$

Input voltages for converter II are:

$$V_{a2} = K_1 V_A - K_2 V_B - K_4 V_B$$
$$V_{b2} = K_1 V_B - K_2 V_C - K_4 V_C$$
$$V_{c2} = K_1 V_C - K_2 V_A - K_4 V_A \quad (7)$$

Input voltages for converter IV are:

$$V_{a3} = K_1 V_A - K_2 V_C + K_3 V_A$$
$$V_{b3} = K_1 V_B - K_2 V_A + K_3 V_B$$
$$V_{c3} = K_1 V_C - K_2 V_B + K_3 V_C \quad (8)$$

Input voltages for converter V are:

$$V_{a1} = K_1 V_A - K_2 V_C - K_4 V_C$$
$$V_{b1} = K_1 V_B - K_2 V_A - K_4 V_A$$
$$V_{c1} = K_1 V_C - K_2 V_B - K_4 V_B \quad (9)$$

Constants K_1-$K_4$are calculated using (1)-(9) to obtain the required windings turn numbers to have the desired phase shift for the three voltage sets:

$$K_1 = 0.67871 \ , K_2 = 0.24 \ , K_3 = 0.17943 \ , K_3 = 0.22966 \ . \quad (10)$$

B. Design of Autotransformer for Retrofit Applications

The value of output voltage in multipulse rectifiers boosts relative to the output voltage of a six-pulse converter making the multipulse rectifier inappropriate for retrofit applications. For instance, with the autotransformer arrangement of the proposed 30-pulse converter, the rectified output voltage is 3% higher than that of six-pulse rectifier.

For retrofit applications, the above design procedure is modified so that the dc-link voltage becomes equal to that of six-pulse rectifier. This will be accomplished via modifications in the tapping positions on the windings as shown in Figure 3. It should be noted that with this approach, the desired phase shift is still unchanged. Similar to section 2part1, the following equations can be derived as:

$$|V_S| = 0.97\,|V_A| \quad (11)$$

Accordingly, the values of constants K_1-K_4 are changed for retrofit applications as:

$$K_1 = 0.66262 \ , K_2 = 0.23438 \ , K_3 = 0.17515 \ , K_4 = 0.22415 \ . \quad (12)$$

The values of K_1-K_4 establish the essential turn numbers of the autotransformer windings to have the required output voltages and phase shifts.

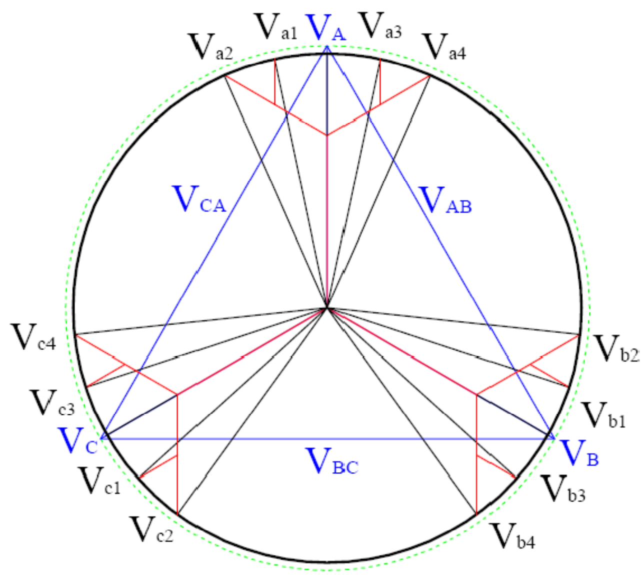

Figure 3. Phasor diagram of voltages in the proposed autotransformer connection alongwith modifications for retrofit arrangement.

To ensure the independent operation of the rectifier groups, interphase transformers (IPTs), which are relatively small in size, are connected at the output of the rectifier bridges. With this arrangement, the rectifier diodes conduct for 120 per cycle. The kilovoltampere rating of the autotransformer is calculated as [4]:

$$kVA = 0.5 \sum V_{winding} I_{winding} \tag{13}$$

Where, $V_{winding}$ is the voltage across each autotransformer winding and $I_{winding}$ indicates the full load current of the winding. The apparent power rating of the interphase transformer is also calculated in a same way.

3. Matlab-Based Simulation

Figure 4 shows the implemented ac-dc converter with DTCIMD in MATLAB software using SIMULINK and power system block set (PSB) toolboxes. In this model, a three-phase 460 V and 60 Hz network is utilized as the supply for the 30-pulse converter. The designed autotransformer is modeled via three multi-winding transformers.Multi-winding transformer block is also used to model IPT.

At the converter output, a series inductance (L) and a parallel capacitor (C) as the dc link are connected to IGBT-based Voltage Source Inverter (VSI). VSI drives a squirrel cage induction motor employing direct torque control strategy. The simulated motor is 50 hp (37.3 kW), 4-pole, and Y-connected. Detailed data of motor are listed in Appendix A. Simulation results are depicted in Figs. 6-15. Power quality parameters are also listed in Table I for 6-pulse and 30-pulse ac-dc converters.

4. Results and Discussion

Matlab block diagram of 30-pulse ac–dc converter system simulation, as shown in Figure 5. Figure 6 depicts five groups of 3-phase voltage waveforms with a phase shift of 12 degrees between the same voltages of each group.