



# **A Review on Multiphase System for High Power Industrial Applications**

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**ABSTRACT:** The electric sector is witnessing a transformation from a three phase to multiphase system owing to various advantages offered by multiphase system or even termed as high phase order systems. The multiphase system application in terms of generation, transmission, utilization is increasing based on the fact that there is a need to explore the new multiphase technology. This paper deals with multiphase technology in the areas of multiphase generation, multiphase transmission and various machines based on multiphase technology. Apart from this various modes of multiphase generation technologies, inverter (AC-DC-AC), Matrix Converter and passive transformation using transformer are also discussed.

**KEYWORDS:** Multiphase machine, multiphase transmission, passive transformation, multiphase inverter, matrix converter.

## **I.INTRODUCTION**

The research in multiphase system has achieved a lot of attention in last decade because of prospective benefits obtained by multiphase system. Increment in the power rating of electrical equipment has been the main technical way to achieve the goals in electrical engineering field, that has led to bulkier size of machines, ultra high voltages levels for transmission (UHV), the multiphase system has lead to an alternative way to achieve the goals with smaller size, reliable operation, lower voltages levels. The multiphase system can be basically classified as shown in fig.1.

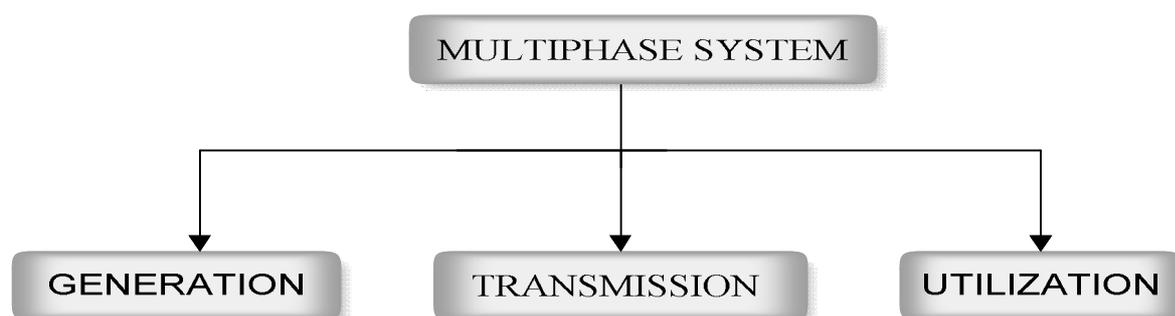


Fig.1: Classification of Multiphase System.

The multiphase generators outperform three phase generator with high torque density, higher reliability, smoother torque, lower size, robustness apart from the advantages stated multiphase machines open up new and interesting avenue in what relates their design, winding connections and control strategies and one of the dominant features is that it can operate even under faulted single phase. The investigation of multiphase system is in infancy stage yet extremely important finding are reported in literature which exhibit technical and economic feasibility of multiphase generation. Due to above mention advantages multiphase generators are currently used in wind generation, marine power generation [1], and hydro power generation [3]. The multiphase power generation is carried out by synchronous generators [1-2], and induction generators [3-4].



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In order to keep pace with the ever increasing load demand increasing the voltage level and transmitting the required power has led to ultra high voltage (UHV) transmission. Due to extremely high voltage level, transmission of power certain challenges are introduced such as strong electric field with possibility of biological effects, radio and audible distortion, visual pollution, tighter transmission corridor. To all these challenges faced multiphase transmission provides a unique solution. Multiphase transmission using six phase, twelve phase and twenty four phases are being studied challenges faced for implementing them are multiphase circuit breaker, multiphase transformer, and multiphase relay coordination is at research stage. Referred papers deals with multiphase transmission [5-10].

The use of multiphase machines have increased due to their inherent advantages provided over three phase motors. The multiphase machines have a higher reliability index and improved energetic performance compared to three phase machines or direct current machines. The multiphase machines find applicability in Hybrid Electric Vehicles, Aircraft Application, Electric Ship Propulsion, and High Power Industrial Applications. Advantages exhibited by multiphase machines over the three phase machines are

- a] Lower space harmonics content field is produced by the fundamental stator currents.
- b] The frequency of lowest torque ripple component proportional to  $2n$ , increases in multiphase machines.
- c] The flux and the torque control of machine are attained by two currents.

As a result there is reduction in the harmonic content in the MMF, noise from the machine reduces and efficiency can be higher than three phase machine additional features offered by multiphase machines are utilization of more than three phases enables decentralization of power across a larger no of inverter legs thus lower rating power semiconductor devices can be used. The multiphase machine can work as long as there is no more than  $(n-3)$  faulted phases but on counterpart three phase machine cannot work even if a single phase is faulted [11].

## II. MULTIPHASE TECHNOLOGY IN GENERATION AND UTILIZATION

Multiphase technology is playing a vital role in electric power generation as the three phase alternators are connected to grid, Multiphase generators can be connected to grid using multiphase transformers or power electronic devices such as rectifier for DC networks and inverters for AC networks, AC/AC converters for ac networks. The dc system is preferred over ac system in isolated power systems like marine and aeronautical applications, application of DC distribution network allows the generator to operate at fixed frequency which makes the generator to rotate at different speeds depending upon the load. This enables optimization of fuel consumption and minimizes pollution emission of prime mover and the generator can be operated in the vicinity of maximum efficiency. These advantages makes dc distribution network suitable for on board supply for marine and aeronautical application, this if coupled with multiphase generators reduces size of the generating unit. Brushless alternators as a substitute for dc generators can be applied to supply DC power grid through AC/DC converters. The simplest design configuration for a alternator – rectifier system consist of a three phase alternator connected to a three phase rectifier system. Similar system can also be applied with a multiphase generator feeding  $n$  number of AC/DC converters.

### A. Multiphase Option in High Power Electric Machines

Multiphase electric machines are playing a vital role in today's high power applications. The inverter-fed motor, for instance; increasing its power rating above certain limits, which exceed the maximum capability of a single inverter unit, necessarily implies using more than one inverter and a natural consequence of such choice is that the machine stator needs to be multiphase with more than three phases. In addition to power rating enhancement reasons, also reliability issues play an important role in pushing towards multiphase design options; the fault tolerance, which is intrinsically guaranteed by a number of phases higher than three, is an extremely important requirement in many safety-critical applications such as vehicle propulsion and also in many industrial areas where a drive stop following a fault may cause remarkable economic or material damages.

### B. Power Decentralization

In multiphase machine the same design practise cannot be followed rather a different approach is to be followed than a three-phase drive, required to deliver a power  $P$  megawatts to the load; losses excluded, the same power  $P$  is to be supplied by the connected inverter, each phase of which is there by demanded to deliver a power  $P/3$ . When  $P$  exceeds some certain limits, the available power electronics technology may become insufficient to achieve such power rating for a single inverter phase. This may be due to single power switch component current or voltage capability limits or to the limit in the number of series-connected or shunt-connected switches that can be included in a phase [12]. As a consequence, it may become mandatory to split the overall inverter-supplied power  $P$  into a higher number of phases.



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Such a power segmentation can be achieved, for example, using multiple ( $N$ ) three-phase inverters, each rated  $P/N$  megawatts, instead of a single converter or still using a single inverter but equipped with  $n$  phases ( $n > 3$ ), each.

### C. Reliability and Fault Tolerance

The advantage to use multiphase option guarantees higher system reliability and fault tolerance. In fact, in case of a faulty phase, the multiphase system is capable of continuing operation, even without changes in control system strategies, although with degraded operation and at reduced power. This is an essential requirement for safety-critical applications such as in vehicle electric ship propulsion drives, and also in those cases where a drive trip and the consequent driven equipment stop causes important economic losses due to production discontinuity as happens in LNG production plants. It is also intuitive and experimentally proven that the higher the number of stator phases the less the degradation and the power de-rating that is to be expected following a fault on a machine phase, Therefore, increasing the number of phases is a provision which generally increments system fault tolerance, in the sense that it reduces the effect of the fault in terms of machine performance.

### D. Performance Analysis

It is well known from multiphase machine classical theory, that increasing the number  $n$  of stator phases enhances the harmonic content of the air-gap flux density field, making its waveform closer and closer to the sinusoidal profile as  $n$  grows. This can be easily explained because the harmonic rotating fields sustained by different phase sets in a multiple star machine undergo a beneficial mutual cancellation effect. Descriptions of this phenomenon in analytical and quantitative terms are proposed in [13]. The benefits which originate for the better air-gap flux waveform due to a high number of stator phases are mainly the following:

- 1). Reduction of rotor losses due to flux pulsations and following induced eddy currents in rotor circuits field, dampers if present and permanent magnets, if present.
- 2). Improvement of torque quality for reduced amplitude and increased frequency of torque pulsations.

The first advantage is especially important for high-speed multiphase electric machines equipped with permanent magnet rotors, permanent magnet eddy current losses tend to increase as the speed grows. The latter benefits are crucial in those applications where the multiphase machine is subject to strongly distorted phase currents and limits are imposed on the maximum allowed torque.

## III. MULTIPHASE TRANSMISSION

Constructing a new transmission line is becoming a challenging job due to environmental laws, licensing issues, high cost of land, acquiring right of way (ROW), and the power demand is increasing and bulk power generation stations are located in remote areas. Transmission lines are the links that connect loads with the generating station. The power transmission capability of a transmission line is achieved by using the higher voltage level, it was the easiest way and that has led electrical systems to reach ultra high voltage levels in transmission. In turn to tackle the problem multi phase transmission provides an alternative solution for bulk power transfer.

The multiphase transmission concept was presented by Barnes and Barthold in 1972 at CIGRE meeting. It has shown that the power transfer capability of multiphase transmission is much higher than compared with three phase transmission capability. Thus optimum utilization of the transmission line or concern over right of way is utilized using multiphase transmission without increasing the space requirement.

### A. Steady State Analysis of Multiphase Transmission Line

The feasibility analysis of high phase order transmission [5] by Stewart and Wilson the part-I deals with steady state considerations were in three phase, six phase, twelve phase and twenty four phases are compared quantitatively in terms of nomenclature of system voltage, steady state system operation and electrical and environmental aspect of radio noise, audible noise and electric field at ground level are studied. Important findings for steady state parameter demonstrates

- 1). Phase to ground voltage is appropriate for system voltage definition for multi phase system, as compared phase to phase voltage for three phase counterparts.
- 2). Symmetrical component method can be implemented for multiphase system for evaluating impedance.
- 3). Thermal line loading increases proportional to phase order while surge impedance loading increases at a lower rate.

### B. Insulation Requirement and Overvoltage of Multiphase Transmission Line.



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The over voltage and insulation requirement for multiphase line are considered in part-II by Stewart and Wilson [6] the impacts of phase clearances and insulation requirement on multiphase transmission lines are evaluated. The phenomena of over voltage due to lightening, interphase coupling and fault over voltages are considered along with the effects of wind, ice, and fault current on phase clearances are considered.

### C. Fault Analysis of Multiphase Systems

The major challenge for implementing a multiphase transmission line is implementing a protection scheme for which detailed fault analysis of multiphase system is to be considered. The fault analysis of a six phase line is considered in [7] were in the first part deals with the theory of symmetrical component development for of six phase systems and second part deals with symmetrical and unsymmetrical fault analysis of six phase transmission line. Another fault analysis problems relates to power flow and stability mainly voltage stability is dealt in [8] were in performance characteristics of multiphase transmission line particularly six phase and twelve phase is compared with the three phase counterparts. Performance characteristics for multiphase transmission line such as load end real and reactive power operating contour maps, reactive power loss characteristics, voltage power under loading characteristics, reactive power requirement characteristics, optimal reactive power at voltage stability limit, shunt capacitive at voltage stability limit using load dependent characteristics of voltage loadability curves are created and their qualitative and quantitative analysis is carried.

### D. Economic Viability of Multiphase Transmission Line

Economic feasibility plays an important role in implementing a multiphase transmission line. An economic comparison of a six phase line constructed, the study compares a 115 kV double circuit three phase line with a 66 kV six phase transmission line which demonstrates six phase can be a cost effective solution to address problems of right of way along with it effect of losses incorporated in the economic evaluation of multiphase transmission line [9].

### E. Test Line And Hardware Developed.

In order to test the feasibility experimental six and twelve phase transmission lines were developed by power technologies inc. 138 kV double circuit line to six phase line studies were carried out by Allegheny Power Company in association with West Virginia University, USA . Primary investigation in India are started by Central Power Research Institute (CPRI) Bangalore, under which examination of 462 kV six phase line, as a alternative to 800 kV double circuit three phase transmission line, as well as converting exiting 220 kV and 400 kV double circuit line to six phase transmission lines are in research stage[10].

### F. Advantages:

In last decade a notion has gained momentum that bulk power transfer is possible using multiphase transmission. The advantages offered by multiphase transmission are[8]:

1. Power handling capability of multiphase system is higher than the three phase system.
2. The voltage stability of multiphase system is higher than three phase system.
3. Reactive power losses are less in multiphase system compared to three phase system.
4. Reactive power requirement reduces with increased number of phases.
5. Steady state stability limits are higher for multiphase system as compared to three phase system.

Though the research in multiphase transmission is in infancy stage once practicability attained will offer bulk power transmission with lesser voltage level and optimum utilization of right of way, the over head equipment used will have compact and pleasing structures with lesser losses and less initial cost on the equipment. The challenges faced in practical implementation of multi phase transmission line are implementation of protection scheme with increased phases increases the no of protection equipments, transformer for multiphase conversion, fault analysis tools. In further part various modes of multiphase generation will be dealt.

## IV. MODES OF MULTIPHASE GENERATION

Increasing the no of the phases enhances the reliability and introduces a complex power converter. A multiphase supply can be obtained by various ways as shown in fig 2.

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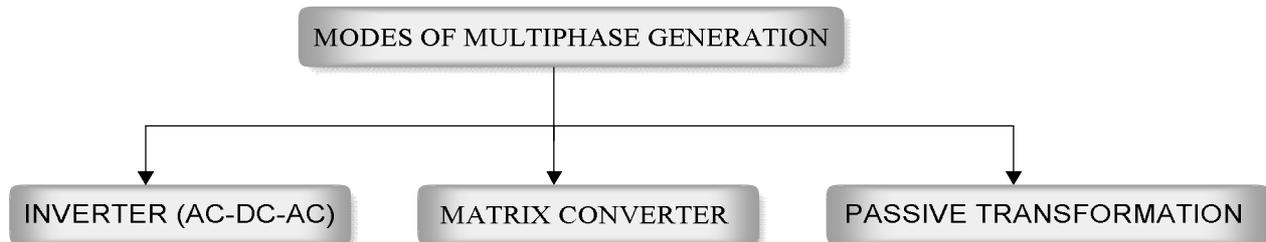


Fig.2. Modes of Multiphase Generation.

## A. Inverter

A multiphase supply can be indirectly converted by converting three phase AC supply to DC supply and then by multiphase voltage source inverter can be used to generate n-phase output [13]. The system is simple but many challenges are faced such as conversion from ac-dc-ac reduces efficiencies and makes system bulkier along with problem of harmonics injected in the system. This type of system are particularly used in multiphase drive system increasing the phases one can reduce the amplitude and increase the frequency of torque pulsation in the drive this ensures satisfactory performance of the mechanical system of the inverter-fed motor even at lower speeds, using a multiphase drive system, inverters with large power rating can be realized with existing semiconductor device. The situation arises when the power requirement exceeds certain limit of the available power electronic system may become inadequate to deliver power using a single unit this may be because of single power electronic switch current or voltage capability limits or due to limit in series connected or shunt connected switches that can be included in a phase as a result it becomes mandatory to split the overall inverter supplied power into a higher number of phases such a power segmentation can be achieved using multiple inverters separately for a different phases of a multi phase machine drive. The multiphase drive system is likely to remain limited to high power applications because of increased component count and inverter complexity. An example of five phase inverter fed induction motor has been investigated the key issues in implementing a five phase drive is to ensure a good stator current waveform the means to achieve the given criteria is selective harmonic elimination method and pulse width modulation technique have been investigated in [14]. The use of inverter provides although viable solution but suffers from drawback such as circulating current harmonics due to inverters being parallel connected for high power applications.

## B. Matrix Converter

The grid is normally three phase and multiphase machines require a phase conversion system, matrix converter serves the purpose of direct AC-AC conversion from multiphase to required phase using power electronic switches. Matrix converter can be classified as direct matrix converter and indirect matrix converter. Direct matrix converter is capable of converting ac voltage to ac voltage with different number of phase, amplitude and frequency. Matrix converter have significant advantages over traditional AC-DC-AC converters such as bi-directional power flow, controlled input power factor, nearly sinusoidal input and output waveform, output current amplitude and frequency are controlled and lack of dc link capacitor for energy storage not required along with it matrix converter are compact in size along with the advantages certain disadvantages are encountered such as limited maximum voltage transfer ratio to approximately 87% and higher no of semiconductor devices employed as compared to counter part of traditional AC-DC-AC converter increasing the number of semi conductor devices increases the complexity of the controller. A three phase to five phase matrix converter generally employed in wind turbines as the grids are three phase and the machines are multiphase it employ fifteen switches as output and input phases are interconnected through a bidirectional switches and there are  $2^{15}$  expected switching states though by applying constraints and appropriate control strategy the controlling of matrix converter is carried out in [15].

## C. Passive Transformation:

The passive transformation refers for change in no of phases by using static device namely transformer. The earliest record of phase transformer date back to 23<sup>rd</sup> February, 1894, when S.P.Thomson read a paper before the royal institution [16], another breakthrough was given by C.F.Scott were two phase alternator was connected to the three phase grid [17], even today Scott connected transformer are used in traction applications. Passive transformation from m phase to n phase on a k limbed transformer is briefly described in [16] were the passive transformation theory is



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discussed and certain examples of phase transformation are demonstrated. Earlier the need was limited for three, two phase with two to three phase Scott connection mostly used in America and leblanc connection favoured in European continent, with the multiphase machines turning out in last decade various attempts are made to use transformer for driving multiphase machine as they gives a cost effective solution by using a multiphase transformer. Another advantage are complex control algorithm as in case of power electronic converter not required such transformers are finding applicability for multiphase generation, transmission, utilization. The method mentioned in [16] can be simply states as first the given phases are transformed in  $(\alpha\beta)$  planes and one zero sequence plane using Clarke's transformation, then the transformed  $(\alpha\beta)$  planes are converted into given number of phases

D. *Various Multiphase Transformers:*

(1) *Three phase to Five Phase Transformer:*

The paper [18] proposes a connection scheme to transfer three phase to a five phase output. The connection scheme consist of three primary winding and eight secondary winding connected to give five phase output along with it phasor diagrams and turns ratio of each coils are mentioned and the results are validate using simulation and experimental results and a five phase motor under loaded condition by using the five phase transformer

(2). *Three phase To Five Phase Using Scott Connection:*

The paper [19] analyses different connection scheme to obtain the five phase supply using passive transformation. Two existing connection scheme in literature are presented and third connection scheme is proposed in paper based on the Scott connection to obtain five phase output. The first connection represent conversion of three phase to five phase three limbed transformer with three primary winding coils and fifteen secondary coil connected to give five phase output. the second connection is similar to that in [18] with fewer no of turns, and balanced primary input voltage the third connection is based on Scott connection with same copper content with the first one but with only two magnetic cores reduces the overall volume of transformer by 23.6% approximately, base on all the three connection scheme the general per phase equivalent circuit of the multiphase transformer is described, the transformer is designed, built and experimental results are demonstrated.

(3) *Three phase to seven phase transformer:*

The connection scheme uses the similar approach as discussed in [18,19] with a phase difference of  $51.43^\circ$  along with it phasor diagram and turns ratios are described. The connection scheme is simulated and experimentally evaluated. The proposed connection scheme is expected to be used in drives and multiphase application [20].

(4) *Three phase to ten phase transformer:*

Three phase to ten phase transformer basically implies dual five phase supply to run two five phase induction machines. An open ended five phase induction machine is run on the sinusoidal output of the three to ten phase transformer. Another application lies in multiphase power transmission and rectifier system analytical results are validated using simulation and by experimental approach [21].

(5) *Three phase to Nine Phase Transformer:*

The multiphase transformer applications for conversion into DC power through rectifier with 18 pulse rectification with less than 0.8% ripple factor is simulated in paper [22].The multiphase transformer is simulated in orcad software and the phases difference of  $40^\circ$  this type of transformer find applicability in railways, aerospace and automobile industry.

## V. CONCLUSION

The research in last couple of decade indicates the use of multiphase technology due to its technical and economical advantages over the conventional three phase technology. The need for growing power levels, reliability, and performance in multiphase technology would lead the design engineers to increase the number of phases. The multiphase technology is opening up new avenue in terms of design and implementation of multiphase technology.

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