DSIM for Electric vehicles applications

Dr.Anagha R.Soman, Associate Professor, Electrical Department, MMCOE,Pune
ORCiD ID: 0000-0003-3827-1810

Abstract

The latest developments in the research area are mostly confined to designing and developing of electrical machines, drives and control in concern with renewable energy is the most happening area in the current scenario. This has gained popularity and importance recently, since many of the developed countries like France; Germany etc. have already declared the deadlines as 2030 to shift completely on to non-conventional energy sources. Hence this area of renewable energy is being explored as one for the most practical and useful applications. The induction motor has become the workhorse of industry because of robust design and simple constructional features, good overload capacity, low capital cost and maintenance, small slip and satisfactory performance under all working conditions. With the latest developments in Power Electronics, Digital Control Theory (DCT) and Computer-Aided Design (CAD) and availability of better materials, the induction motor has proved itself as the most versatile electrical machine in the industries in constant as well as variable speed applications. This chapter basically deals with innovative changes in the design of conventional induction motor resulting in operations suitable for wide range of torque-speed characteristics such as solar/ hybrid electric vehicles. This is achieved by providing one more winding in stator core.

These two windings can be wound for similar/ dissimilar number of poles [1]. On the basis of rotor construction, the conventional induction machines can be broadly categorized into two types, namely standard die-cast squirrel cage rotor and wound rotor. Both of these rotors have their own pros and cons. Squirrel cage induction motors, varying from minimum rating like fractional kW to several thousands of kW, have numerous applications. Squirrel cage Induction machines enjoy versatile applications in various fields and have covered 90%

electrical machines market. Induction machines have typical torque-speed characteristic in which speed is almost constant and the torque can be varied by varying the rotor resistance. However, in case of squirrel cage induction machines, the variation of rotor resistance is not easily possible. Stator side control is also feasible for change in speed. These methods are: pole changing, supply frequency control, supply voltage control, voltage/frequency control, and insertion of an additional resistance / impedance in stator circuit.The conventional speed control methods discussed above suffer from certain operating issues such as non-flexibility to achieve desired Torque-Speed characteristics of the motor as per the load requirement for a specific application. Also in all such strategies adopted, the electrical frequency changes with the mechanical speed ($n = (2f/p)(1-s)$). Hence, a flexible (adjustable) control over Torque-speed is not achievable. One of the solutions to these issues can be use of Voltage Source Inverter (VSI) fed Induction machine. However, this method injects harmonics in the system and reliability is reduced and cost is increased. Also, Variable Frequency Drives (VFD) need proper filters, to restrict rate of change of voltage (dV/dt) up to 6 kV/ µS which otherwise may damage the insulation. In view of different control schemes discussed in previous sections, it is felt that a Dual Stator-winding Induction Machine (DSIM) will provide a better solution to variable speed applications.

Keywords: Torque-Speed characteristics, DSIM, VSI, DCT, CAD

1.1 Introduction: Background and Driving Forces

India is the third largest consumer of Electrical energy wherein, every individual consumes 800 units per year, though per capita consumption is amongst lowest and the carbon emissions 1.56 % (where an average CO_2 emission is 4%)

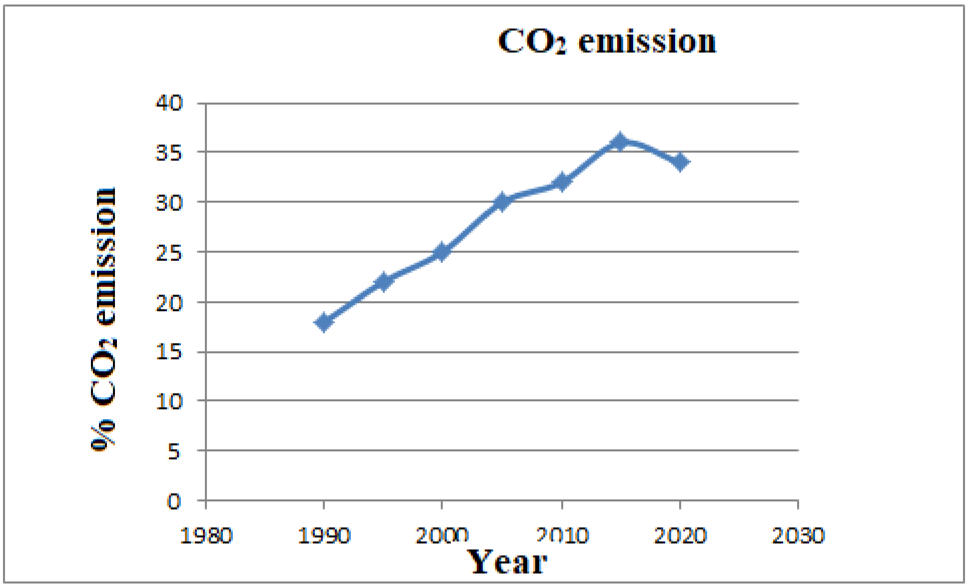

Fig 1.1: Variation in carbon emission over last 30 years

Earth could respire bit easily with the COVID-19 pandemic lockdown around all over the world preventing people coming out of homes. As per the Global Carbon Project's report for 2020 predicted the largest-ever low in carbon emissions from fossil fuels in history as 7%. This is shown in fig. 1.1. Over the years, the awareness of green energy has changed the power consumption scenario drastically even in the developing countries like India. Particularly, the picture in India is that out of the total energy consumption now, Out of 375 GW installed capacity. 88% of that from fossil fuels is reduced by 2%. Also there is a significant decrease in the oil consumption and share of renewable energy in the overall electrical energy consumption is going up. Thus there is a change of focus from fossil fuels to renewable sources. Specifically, thermal energy contributing to 220 GW (more than 65%), hydroelectric energy 44 GW, and gas based energy sources 25 GW, nuclear energy 6.7%. From the year 2005 onwards, per capita consumption is increased from 16.3 units back in 1947 to 1208 units in last year. In Maharashtra, generation is reached to 30000 MW, but demand is increasing day by day. Different challenges faced are rapidly decreasing stock of coal (shortage of raw material to the generating plants), financial capability of utilities, political will, and clean disruption technology. Globally, India is on fourth place (After china, USA and Germany) in the radiation emission. Technology based disruption is really a need of an hour. One of the prominent solutions is development in electric vehicles among otters such as cane in architecture of technology, Digital technology, smart grid, generation on basis of demand etc. It is expected that by 2030, clean disruption swiftly will take place. Big companies such as general motors, Volkswagen, KIA, Tesla, Nissan, Tata are working on research and development of Electrical vehicles. Electric vehicles will replace fully the IC engine technology by 2030. We have to change our life style according to the trends in technology was one of the lessons learnt from the following examples 1) Nokia market was taken over by smart phones despite superior and robust hardware 2) Kodak was replaced by Sony digital camera in the year 2000. As far as the cost and maintenance is concerned, there are 998 parts in IC engine but just 28 in Electrical vehicles. The next revolution expected is a Driverless car will replace other vehicles.

For an application in electric vehicles, electric motors should have comprehensive control on speed , high torque and fast speed response even at lower speeds and constant power in high speeds. These features are available in DC machines as well as Induction machines. The induction motor being the workhorse of industry has robust design and simple constructional features, good overload capacity, low capital cost and maintenance, small slip and satisfactory performance under all working conditions. With the latest developments in Power Electronics and Digital Control Theory (computer-aided design) and availability of better materials, the induction motor has proved itself as the most versatile electrical machine in the industries in constant / variable speed applications. This chapter deals with innovative design of conventional induction motor resulting in operations with wide range variable speed. This is achieved by providing an additional stator winding as shown in fig. 1.2

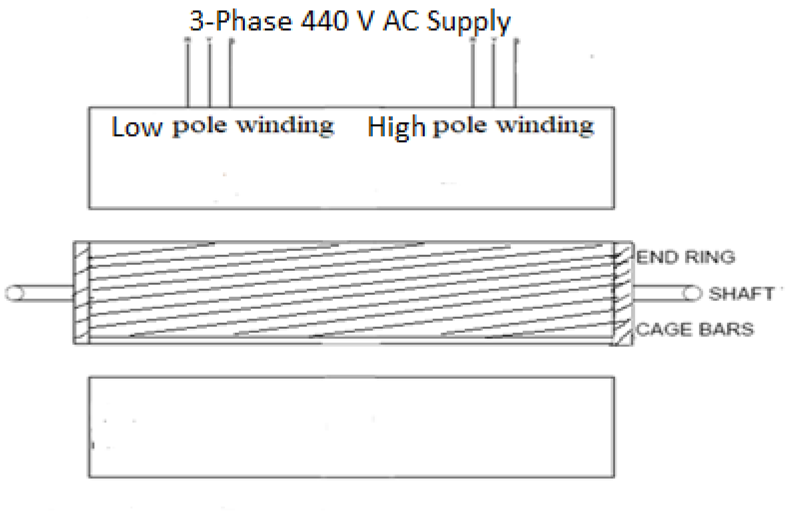

Fig. 1.2 Cut section of DSIM

Concept.1.2 Development of Dual Stator-winding Induction Machine (DSIM)

Induction machines have ruled electrical market since more than one and a half century. The development in the electrical machines is being carried out by improving upon efficiency, power factor, torque to weight ratio, power to weight ratio, dynamic performance of machine, mean time between failures (MTBF), size of the machine and payback period. Researchers are also working on betterment of multi-speed motor drives in areas like reduction in harmonic content of DC link current, smoothening of electromagnetic torque pulsations and improvement in the overall system reliability.

Power electronic frequency converters have brought a Great revolution in the development of electrical machine control that can provide multi-phase systems of voltages and currents, electrical drive systems usage with multi-phase cage rotor induction motors in various industrial applications, is increasing. Among the different drive solutions, one of the most interesting and widely used solutions is the use of dual stator winding squirrel cage induction motor, for applications requiring a smooth speed regulation.

Multi-speed electrical machines and drives (being brushless machines) are found to be superior to the conventional 3-phase machines because of higher power density and fault tolerant capability. Hence this brushless alternative is now receiving attention of researchers in applications like electric vehicles and renewable energy sector. These machines make the system mechanically stronger and require low maintenance. DSIM is a special type of multi-speed machine having squirrel cage rotor and two stator windings housed in same magnetic structure i.e. stator. DSIM is broadly classified as split wound and self-cascaded. There are again two types of the split wound machines, where winding is either split in two equal sections or in two unequal sections. In 1920, the split-wound concept was introduced in case of synchronous generators to improve capability and reliability of a system using such machines. The conventional DSIM has a construction such that the stator winding is divided into two similar windings thus causing mutual coupling between them. This mutual coupling result in drawing very high circulating currents generated even for a small unbalance in supply voltage. Owing to the low impedance to the harmonic currents, the circulating currents are high when supply voltage is non-sinusoidal. This ultimately causes an increase in stator losses and overheating of the machine leading to the higher ratings of semiconductor devices used in control circuits. If the windings are not identical, i.e. the numbers of poles are different; torques developed by the two windings may oppose each other. This type can further be classified on the basis of phase difference between the two windings. Such a machine has special rotor construction which is too complex to fabricate and faces serious issues in insulating the rotor bars. Because of the cascade connection, the system suffers from low efficiency.

In DSIM, when one stator winding is supplied at rated voltage and frequency and the other at variable voltage, the arrangement controls the speed and torque of the machine over a broader range.

Having no magnet and brushes, DSIM has a wide scope in applications such as extracting renewable energy, traction drives, Micro grids etc.

The DSIM has two stator windings which share the same machine core and the common squirrel cage rotor winding. DSIM offers a number of advantages like (i) speed sensor-less operation (ii) better reliability (iii) more flexibility to manipulate the resultant torque-speed curve of motor which is implemented by separately controlling the stator currents drawn by each of the two stator windings. Thus, a minimum electrical frequency can be maintained irrespective of the mechanical speed. This feature is especially important to minimize the negative impact of the stator resistance at low-speed operation [1].

Because of the dissimilar number of poles, there is a decoupling effect which in turn makes the DSIM behaves like the two separate induction machines are coupled to the same shaft. Hence, all the control methods used for conventional induction machines apply to DSIM. The two stator windings being totally isolated electrically, fast dynamic response is feasible. The two windings being symmetrical, there is no mutual coupling and hence no circulating currents. In any operating condition, stator frequency of DSIM depends on the slip frequency, rotor speed and the second torque component. Thus, unlike the conventional induction motor, there is no direct correlation between speed and the supply frequency i.e. zero speed does not result from zero supply frequency.

Any ratio of pole numbers can be chosen for the two stator windings; however, to utilize magnetic material to its maximum limit and saturation and extra core losses can be omitted if pole combination is in the ratio 1:3. To reduce magnetic coupling between two stator windings, the windings may have different number of poles e.g. 2 and 6. Both the stator windings are individually supplied either by (i) two different voltage source inverters to get variable frequency at variable voltage inputs or by (ii) two different 3-phase auto transformers to provide variable sinusoidal voltage inputs.

Two different operating modes are considered in the present project. They are synchronous operating mode and asynchronous operating mode.

1.3 Testing and analysis of DSIM

The chapter deals with the design, development, testing and analysis of DSIM. Many researchers have put forth different innovative changes in design of 3-phase induction motor to improve its performance [2]. DSIM is one of such designs in which an additional stator winding is provided whose torque component plays an important role in the speed-torque characteristics of the machine.

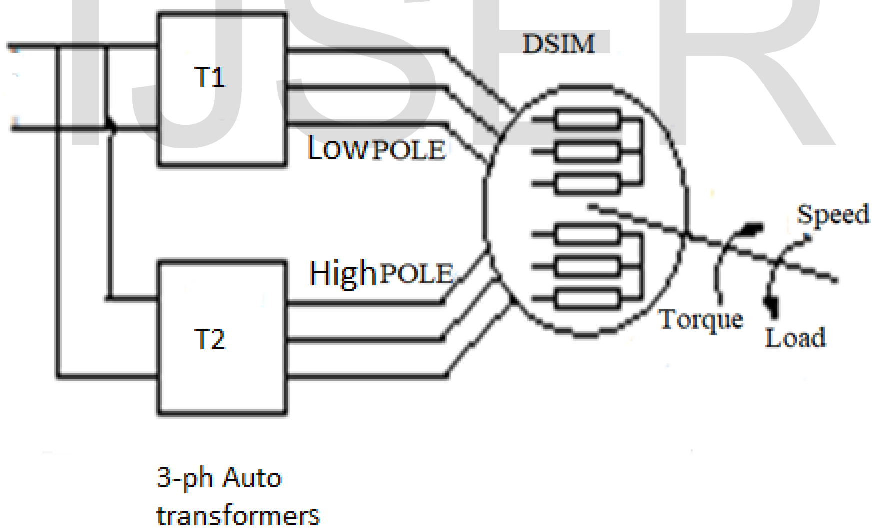

Fig 1.3 Testing of DSIM

The main objective is to obtain a range of torque-speed characteristics using DSIM to be used in traction applications. For the testing purpose, the DSIM is coupled with a DC generator to load it electrically. The details are as under.

To test DSIM prototype for four cases of different input conditions and plot respective torque-speed characteristics. The four cases are as follows [3]:

(i) Variable voltage, constant frequency (VVCF) when both the stator windings produce torques in the same direction.

(ii) Variable voltage, constant frequency (VVCF) when both the stator winding produce torques in opposite directions.

(iii) Variable voltage, variable frequency (VVVF) when both stator windings are in motoring mode.

(iv) Variable voltage, variable frequency (VVVF) when one of the stator windings is in motoring mode and the other in generating mode.

1.4 Results and conclusions of testing

The experimental investigations of prototype DSIM are carried out for various input conditions such as, variable voltage at power frequency and variable voltages at variable frequencies. Also, these two conditions are again tested for the two subcases i.e. (a) additive torques and (b) subtractive torques. Apart from the technical investigations about performance parameters, other factors like (a) vibrations (b) noise (c) temperature rise etc. were also carefully observed during investigations and care was taken to see that they do not cross the permissible limits. It is found that, experimental results are in line with the simulation results.

Experimental results on prototype DSIM have been presented in detail as follows, show a good co-relation with the theoretical curves. From the testing results and analysis [4], it is concluded that variation in voltage supplied to the two stator windings, results in change in the resultant torque developed by DSIM. Four cases as stated in section 1.3 are considered in this.

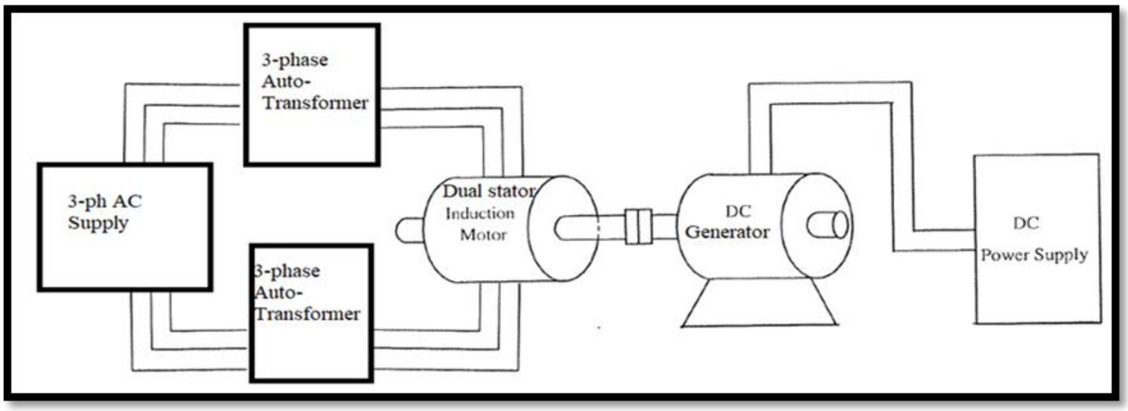

Fig. 1.4 Experimental set up for cases 1 and 2

<u>Case I</u>: Low pole winding is supplied at rated voltage and rated frequency and high pole winding is given variable voltage at rated frequency.

Again, there can be two subcases here: i) Both the machines rotating in opposite direction

ii) Both the machines in same direction.

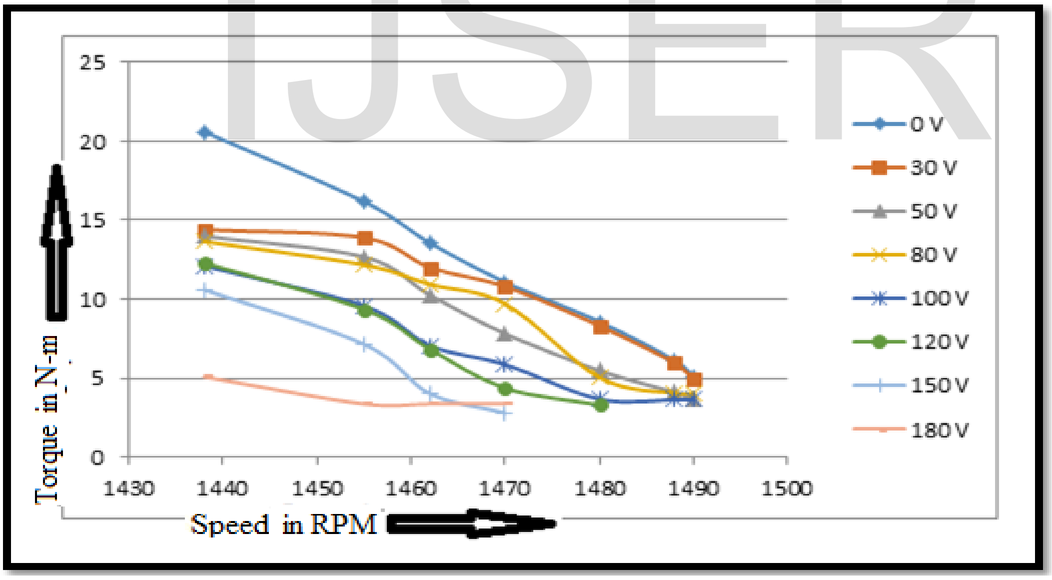

Fig. 1.5 Family of Torque-speed characteristics when low-Pole winding supplied at 400V and high-Pole winding supplied at variable voltages (opposite direction)

From the above figure, (fig. 1.5) it can be concluded that when low-pole winding is fed with rated voltage and rated frequency and voltage supplied to high-pole winding is varied from zero to 180 V,

- The range of torque variation is maximum (5 to 25 N-m) when low-pole winding is fed with rated voltage and high-pole with variable voltage (opposite direction).
- The maximum speed around which machine operates in this case is around the synchronous speed of low-pole winding as it is supplied with rated voltage.

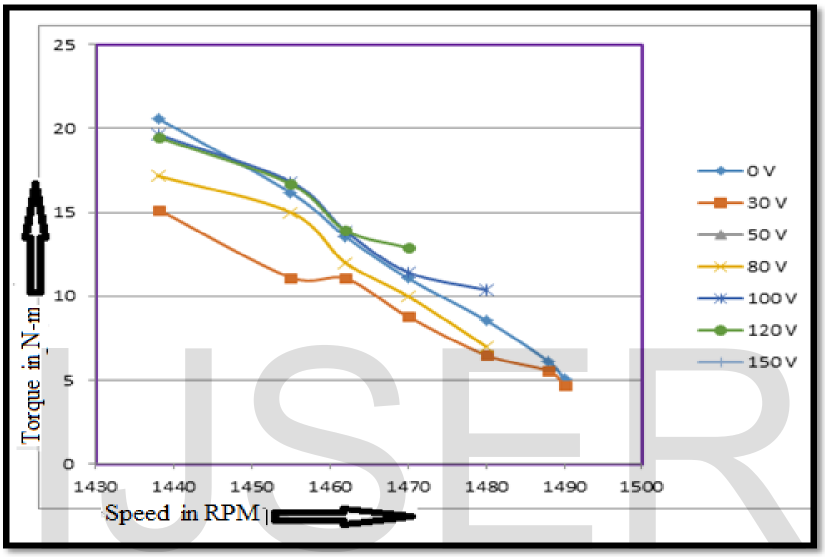

Fig. 1.6 Family of Torque-speed characteristics when low-Pole winding supplied at 400V and high-Pole winding supplied at variable voltages (same direction)

From the above fig. 1.6, it can be concluded that when low-pole winding is fed with rated voltage and rated frequency and voltage supplied to high-pole winding is varied from zero to 150 V (same direction),

- The range of torque variation is maximum (15 to 22 N-m) when low-pole winding is fed with rated voltage and high-pole with variable voltage (same direction).
- The maximum speed around which machine operates in this case is around the synchronous speed of low-pole winding as it is supplied with rated voltage.

Case II: High pole winding is supplied with rated voltage rated frequency and low pole winding is given variable voltage at rated frequency

Again, there can be two subcases here: i) Both the machines rotating in opposite direction

ii) Both the machines in same direction

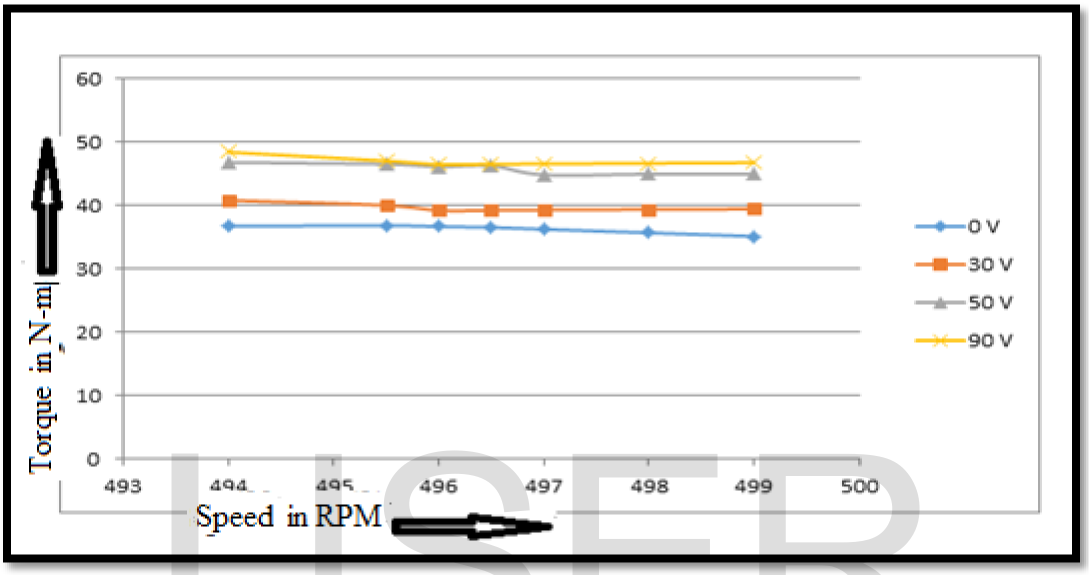

Fig. 1.7 Torque-speed characteristics when 12-Pole is supplied at 400V and 4-Pole at 120 V (opposite direction).

From the fig. 1.7, it can be concluded that when high-pole winding is fed with rated voltage and rated frequency and voltage supplied to low-pole winding is varied from 0 to 90 V (opposite direction),

- The range of maximum torque variation is (38 to 48 N-m) when high-pole winding is fed with rated voltage and low-pole with variable voltage (opposite direction).

The maximum speed around which machine operates in this case is around the synchronous speed of high-pole winding as it is the one supplied with rated voltage.

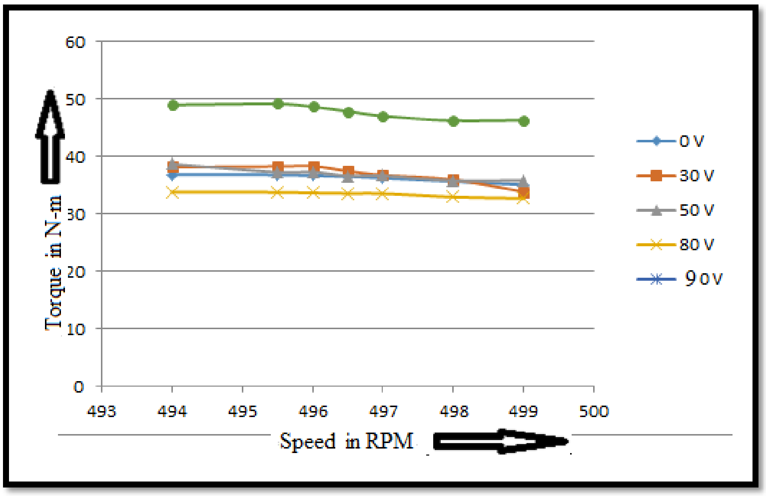

Fig. 1.8 Family of Torque-speed characteristics when high-Pole winding supplied at 400V and low-Pole winding supplied at variable voltages (same direction)

From fig. 1.8, it can be concluded that when high-pole winding is fed with rated voltage and rated frequency and voltage supplied to low-pole winding is varied from 0 V to 90 V (same direction),

- The range of maximum torque variation is (34 to 49 N-m) when high-pole winding is fed with rated voltage and low-pole with variable voltage (same direction).
- The maximum speed around which machine operates in this case is around the synchronous speed of high-pole winding as it is supplied with rated voltage.

Case III: Low pole winding and high pole winding are supplied with voltage and frequency in the same ratio as poles (synchronous mode)

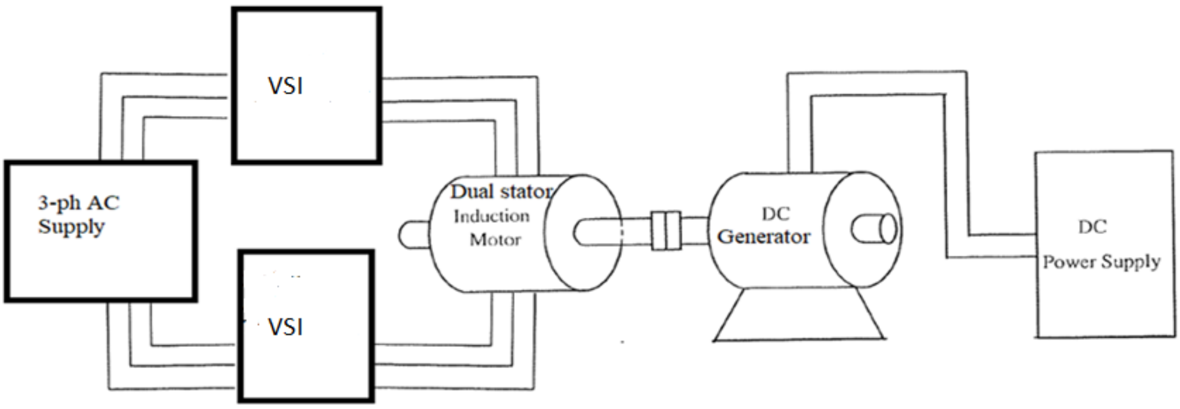

Fig. 1.9 Experimental set up for cases III and IV

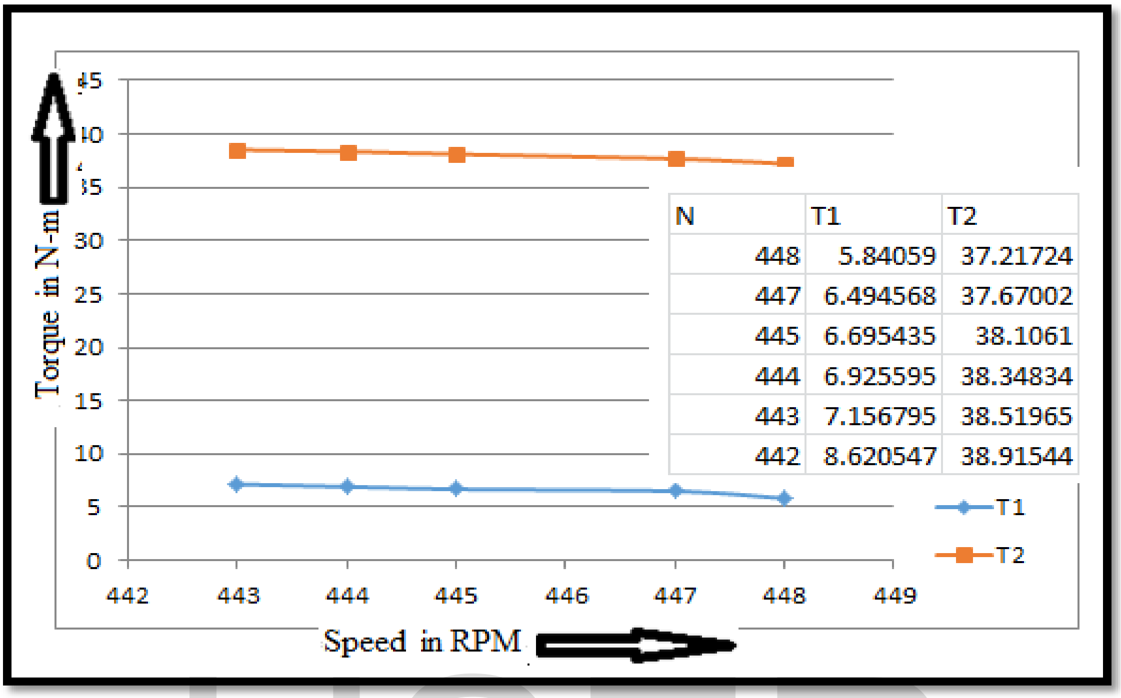

Fig. 1.10 Torque-speed characteristics along with corresponding observations when DSIM in motoring mode.

From the fig. 1.10, it can be concluded that low-pole winding is fed with 15 Hz and high-pole winding with 45 Hz, so that $P_1/P_2=f_1/f_2$.

- In this operation, both the windings operate in motoring mode.
- DSIM is found to be suitable for scalar control.
- Starting current of high-pole winding is almost twice that of low-pole winding.
- The torque contributed by low-pole winding is too small as compared to high-pole.

Case IV: Low pole winding is supplied with very low frequency and high pole winding is supplied at higher frequency (Asynchronous mode)

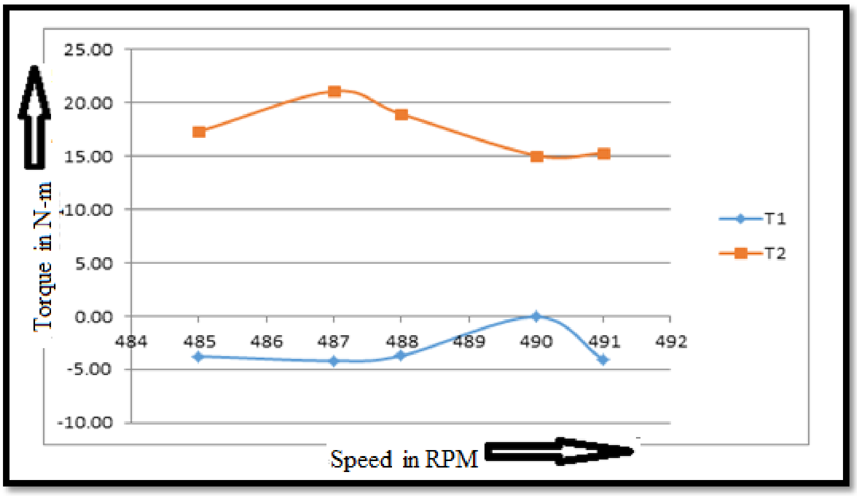

Fig. 1.11Torque-speed characteristics along with corresponding observations with one of the windings of DSIM in generating mode and other in motoring mode.

From the fig 1.11, it can be concluded that when low-pole winding is fed with 4 Hz and high-pole winding with 50 Hz,

- one winding operates in motoring mode and the other operates in generating mode.
- The torque contribution by low-pole stator winding, i.e. T_{e1} is negative in nature and that of high-pole winding i.e.T_{e2} is positive.
- Thus, the low-pole stator winding operates in generating mode and high-pole stator winding continues to operate in motoring mode. Thus, low speed operation can be achieved.
- low-Pole winding can produce a larger torque or even a negative torque.

From the testing results and analysis, it is concluded that variation in voltage supplied to the two stator windings, results in change in the resultant torque developed by DSIM. Figs. 1.5, 1.6, 1.7 and 1.8 show family of the torque-speed characteristics for cases as stated in section 1.3 i.e. i), ii) and iii).

When DSIM is fed with minimum feasible frequency to one winding and the other with fixed frequency (nearby power frequency), the output torque can be adjusted as per requirements of the application. This can be done by regulating voltage and frequency supplied to the windings. This is shown in figs. 1.10. In another operating mode, shown in fig. 1.11, the low-pole winding produces a torque more than that of the load. This extra torque produced is opposed by an equal and opposite torque produced by the high-pole winding. It is evident that, one winding operates in motoring mode and the other in generating mode.

Thus, the DSIM facilitates a wide range of torque-speed characteristics [5] and, unlike conventional induction motor, it is not necessary to be confined to a single torque speed characteristic.

1.5 Summary:

A systematic procedure has been discussed thoroughly in this chapter to generate a family of torque-speed characteristics for different input conditions. Important point to be noted is that, in asynchronous mode of operation, when low-pole winding is fed with minimum possible frequency and High-pole winding with high frequency, low-pole winding operates in generating mode and High-pole winding continues to be in motoring mode.

DSIM is a special case of multi winding Induction machines having two electrically isolated dissimilar windings in stator and standard squirrel cage rotor. A comprehensive review is taken about the speed and torque variation of DSIM. The chapter discussed the machine as strong contender in future for application in electric vehicles.

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