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Modified Circuit Design of VFD for Critical Loads under Single Phasing Condition

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Abstract: *Single phasing condition occurs in three-phase supply when one phase out of three is disrupted. Most of the machines used in the industry are three-phase induction motor Variable Frequency Drive (VFD) for controlling speed and torque. If single phasing occurs, then the system visualizes it as fault and the protection adopted disconnects the VFD from supply. This decreases efficiency of an industry by creating frequent interruption in the process. A lot of work has been reported by earlier researchers for cost saving in case of VFD and mainly kept their focus on designing protection scheme against single phasing. The scholar proposes a modified circuit to make VFD operational under single phasing by designing high value filters for critical load operation. Three phase rectifier circuit has been replaced with 3 single phase rectifiers to remove dependence of phases on each other for load sharing under single phasing. The simulation using MATLAB (2019RA) for designed circuit model produced promising results. When single phasing occurs, the critical load on VFD is automatically equally superimposed on the remaining two healthy phases without reduction in the torque and speed output.*

Keywords: *Single phasing; Variable frequency Drive; Three-phase Induction Motor; MATLAB Simulation*

I. INTRODUCTION

Variable Frequency Drives (VFDs) are used in industries at large scale these days. The motive of saving energy and high torque even at start for induction motor is achieved by using variable frequency drive. Using VFD helps in soft start of IM, reduces the starting current, as well as tear & wear [1]. Power losses in an IM can be decreased by two methods i.e. increasing the flux in case of large loads and in case of light loads by decreasing the flux [2]. The VFD helps in controlling the induction motor by changing flux using supply parameters control. For a particular load, the choice of VFD is based on parameters like- life-cycle cost, initial cost, ease of maintenance, weight, dynamic performance, robustness and environmental acceptability [4]. Winding losses are inevitable during single phasing which necessitates some sort of protection of the motor to disconnect it under such circumstances [5].

In a survey of petroleum industry aimed at investigating the failure rate and cause of failure in motor revealed overheating, mechanical breakage and insulation breakdown are the major initiators of the fault. Besides this unbalanced supply has also been reported as major reason for failure of motor under single phasing condition. However, study related to reliability of VFD's is still inconclusive [14].

As far as detection of single phasing is concerned, it is done by under voltage detection using LCM324 integrated circuit. This system is very economical, efficient and easy to use [6]. Single-phasing detection and classification of the lost phase can be done by using artificial neural networks (ANNs) as well [8].

Two kinds of protection are possible against single-phasing, the first one uses contactors (with over current relays) and the second is the voltage monitor circuit. Of these two, the second offers more protection than the first, as a result of its sensitivity to voltage variation and thus is recommended [9]. Voltage monitoring circuit using PIC16F877 microcontroller has been found to be quite effective [10]. Another proposed circuit is automatic tripping mechanism for the three-phase supply system while single phasing with the help of 555 timer and voltage regulator LM7809 [11]. On line protection system for induction motors during single phasing has also been achieved [12].

Connecting a transformer with three phase zig-zag winding in parallel with star wound three phase induction motor, neutral point of motor winding connected to neutral of main power supply could be an approach to run the drive at full load under single phasing condition [13]. This method calls for high initial investment, high maintenance and needs an additional unit causing unnecessary inconvenience. The proposed modified circuit for VFD requires low maintenance, is cost effective and is solution to the limitations of the above said method.

II. Variable Frequency Drive

Speed and torque of AC motor is controlled or varied by changing input frequency and voltage of the motor using a Variable Frequency Drive (VFD). The speed of drive is controlled smoothly with accuracy as per load torque requirement.

Control methods

Pulse width modulation technique controls the input of an AC motor. PWM pulses generated in the process is being shown in Fig. 1. The gate voltage is the threshold voltage of a transistor/switching device to get it in running condition or make it 'ON'. The carrier frequency (usually 2 to 15 kHz) voltage is rated at or above the gate voltage. A moderate carrier frequency is necessary to achieve smoother output wave and less switching losses. The sign wave i.e. reference voltage can be varied from 0 to 50Hz to change the output frequency. Voltage of reference wave is varied to control the output voltage of the motor [16].

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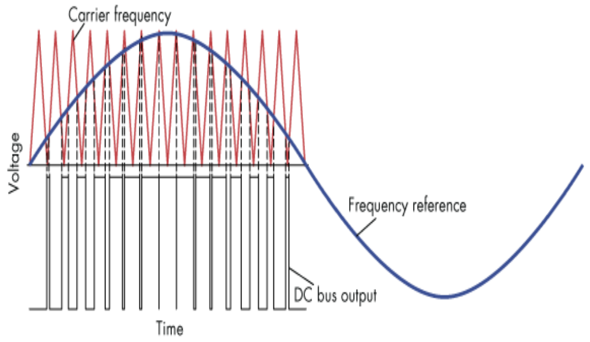

Fig 1. Operation of PWM technique [8].

Four control methods are used for generation of PWM pulses for industrial applications. These are:

1. V/f (volts-per-hertz)
2. V/f with encoder
3. Open-loop vector
4. Closed-loop vector.

NEMA guidelines for adjustable speed drives:

- Motor torque, speed, and temperature: Normally, if winding temperature increases by 10 degrees Celsius above the rated value, the winding insulation life reduces by 50%. VFDs torque output can be controlled by varying motor flux which may lead to production of heat. Therefore, motor should strictly be operated in permissible temperature range [17].
- Operation above base speed: Motor should be operated maintaining V/F ratio constant under base speed. Above base speed, general purpose motors as per NEMA design A and B, are rated for constant horsepower operation up to 90 Hz. Based on approximate peak torque capability, the upper limit for these motors has been derived to be 175% [17].
- Running current: The allowable capability of drive under periodic overloading depends on its response to change in loading condition. Typical drive may specify its overload range as 110% or 150% for 60 seconds [17].
- Voltage stress: As per NEMA MG1 Part 31 for motor insulation systems, 460 V rated motor, need to withstand 1600-volt peak, with rise time of 0.1 microseconds [17].

III. Single Phasing

The term single-phasing is defined as condition when one of the 3 phases is open. The worst possible condition of voltage unbalance for drives is single-phasing. The motor will try to deliver its full power by over drawing current from healthy phases enough to drive the load, if not tripped under single phasing. The motor will continue to drive the load, which may lead to burning of motor winding or if any proper sized fuse is connected in the line, will trip the relay resulting in motor going off the line. The motor overload protection is recommended to be established upon the current drawn by motor under its practical loading condition, rather than the full load rated current rating [18].

Causes of single phasing

Single Phasing can be due to various reasons such as

- one or more out of the three fuses are blown
- one of the contactors is open circuited,
- inappropriate setting of protective devices
- broken motor winding
- breakdown of the supply
- short circuiting in one of the phases of the motor.

Besides these blowing of fuse of feeder or transformer can also contribute to single phasing.

Unbalanced voltage

Overheating due to voltage unbalance is one of the main causes of motor winding damage. Voltage unbalance results in unbalance of current as well, which is around six to ten times of voltage unbalance. This increase in current unbalance causes heating of the motor windings that in turn causes breakdown of the motor insulation. It results in permanent damaging

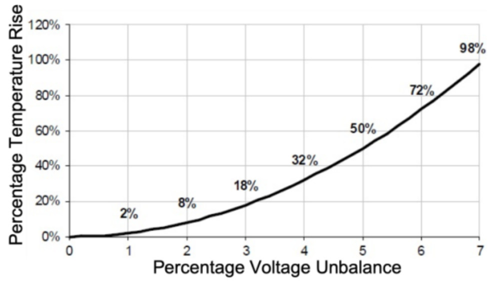

Fig 2. Percent temperature rise due to voltage unbalance [5].

of the motor [19]. Fig 2. shows relation between percentage voltage unbalance and expected temperature rise.

According to NEMA (National Equipment Manufacturers Association) MG-1-1998, motors should be restricted to give rated output only for voltage unbalance of 1%. NEMA MG-1 states that current unbalance of 6-10% can be observed with 1% of voltage unbalance only.

Voltage Unbalance Formula:

$$\%\text{Voltage Unbalance} = \frac{100 * Maximum\ Voltage\ Deviation}{Average\ Voltage}$$

Derating Factor

As per NEMA MG-1, for more than 5% of voltage unbalance, the motors should not be operated. However, to minimize the possibility of damage, motors should be derated to a particular extent. As per NEMA MG-1 Fig.3 shows the variation of derating factor with increase in voltage unbalance percentage [20].

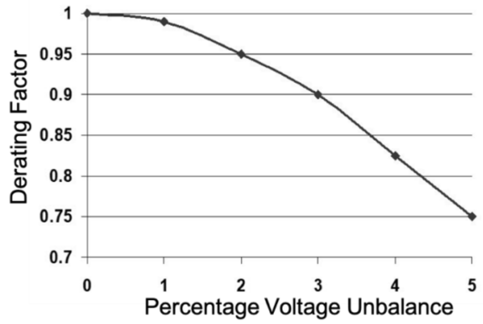

Fig 3. Derating factor for motors per NEMA MG-1 [17]

IV. Modeling and Designing parameters

Some of the problem faced by 3 phase induction motors while running under single phasing are

- loss of self-starting property
- overheating or critical damage to windings due to short circuiting
- increase of current by 2.4 times the average current in the healthy phases
- reduction in speed of motor and fluctuation in rpm
- production of noise and vibrations in motor
- distortion in output of the auxiliary machine attached if any, due to varying speed and torque.

When single phasing occurs, motor is switched off and there is wastage of time in finding the fault. In many industries continuous operation of motor is critical. This problem has been the basis for this piece of research. The main focus was to design and develop an automatic controlled power supply system which could run the motor with same speed and torque during normal and single phasing condition. Our model is designed to address this vital problem of critical loads by making a VFD which can run even under single phasing.

Model proposed has been simulated in MATLAB/Simulink as shown in fig 6. Running the motor with same load requirement under single phasing leads to increased current in other two healthy phases. So, first change required is increased rating of fuses and other protection devices.

Relay design

In this design (Fig. 4) relay block has been used to create a virtual single phasing condition as it trips when short circuiting occurs. The MATLAB based switch is so designed that shifts output from 1 to 0 when current crosses 600 Amp (fault situation). The NOT gate has been used to invert the output of switch, while SR flip-flop stops the circuit from restarting using its special feature of independence of R when S is nil. The step function initiates the relay circuit. Surge currents will be taken care of by this relay. Backup Thermal relay is also used to handle over currents based on I^2Rt (temperature rise) for overload protection.

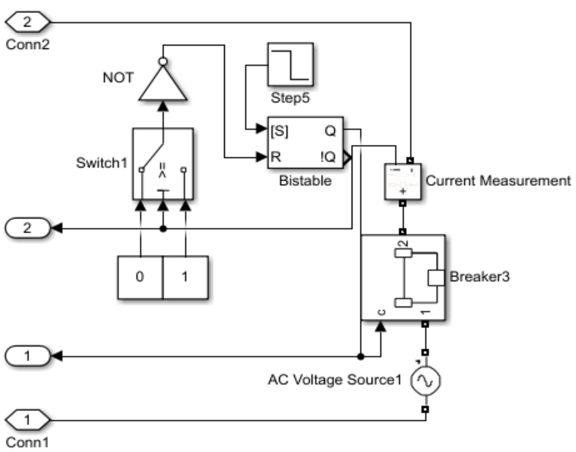

Fig 4. Power Supply and Relay Block

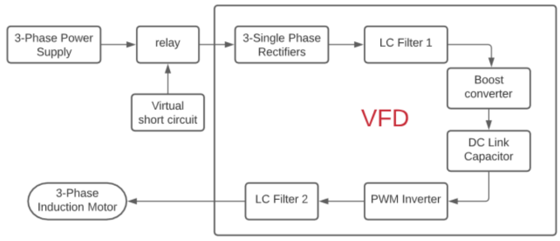

Fig 5. Block Diagram of Modified Circuit for running VFD under single phasing

Table 1. Input Motor Current with 3 Phase rectifier

Condition	Motor Input Current (Amp) at 25Nm (Full load)			Motor Input Current (Amp) at 15Nm (Decreased load)		
	A	B	C	A	B	C
Normal Condition	7.94	8.1	8	4.81	4.85	4.84
Fault in phase A	0	18.77	5.24	0	11.23	4.184
Fault in phase B	5.13	0	18.56	4.581	0	10.88

3-Phase rectifier is generally used in making of VFD's. During single phasing, in 3-Phase rectifier, there occurs lot of misfiring, leading to imbalance in healthy phases. Besides this high input power ripples has been observed in case of single unit of 3-phase rectifier. Table 1 shows motor input current while using 3 Phase rectifier. As per phase sequence, current surges up to 2.5 times the normal current in the next phase to the faulted one have been observed and tabulated in table1. To overcome this current surge in the healthy phases due to single phasing three units of single-phase rectifiers has been used. This balances the input currents drawn from the healthy phases as the three phases are independent of each other. Also the rating of the uncontrolled rectifier components are increased to enable it to carry the total current shared by only two healthy phases. Also the fuse ratings are increased so that it does not blow off during single phasing full-load operation period.

The square wave inverter normally used in VFD creates noise and high ripples in motor torque and speed outputs which is highly undesirable. Thus PWM inverter has been used as a better alternative for the purpose.

Average Modelled (D-controlled) Boost Convertor with 0.45 Duty Cycle, boosts the rectifier voltage from 250 V to 450 V for a PWM inverter to give appropriate output of 400V as input for smooth running of the induction motor. The grounding needed for implementation of boost converter results in inability to fire the negative half of PWM inverter. A DC Link Capacitor has been used to solve this problem, which reduces ripples of the Boost converter as well as helps in dividing the output of rectifier into positive and negative halves.

Rectifier filter is designed to decrease the DC ripples less than 3% THD to match the standards of IEEE (Std. 519-1992 Harmonic Limit Discussion). In case of 3-phase LC filter the required high inductor value makes it non-feasible both economically and size wise. Hence, small inductors of about 0.01H in individual phases are used here. Consequently, Capacitor value is decided by formula.

$$\Delta V = \frac{0.7I}{CF}$$

The frequency is 50 Hz and DC current has been found to be around 26 Amp. Empirically selecting Capacitor value as 0.005 F, the $\boldsymbol{\Delta V}$ comes out to be 12.13, which is under permissible limit.

Ideally the input to the motor should be sine wave which is achieved by resonance between the filter and motor inductance. Theoretically, finding the exact inductor value is a complex job, thus it has been found experimentally by monitoring the input current of the motor. On this basis 0.01 H inductor has been selected for the purpose. Consequently, the choice of the capacitor becomes automatic by using basic resonance formula.

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Here 'f' is 50 Hz, L=0.01H + inductance of induction motor which is around 0.001H, C comes out to be 4.67×10^{-4} F.

V. Simulation Results and Discussion

The AC asynchronous machine used has the following ratings.

3 phase squirrel cage motor, 5.4 HP (4kW), 400 V, 50 Hz, 1430 rpm

Stator Resistance: 1.405ohm, Inductance: 0.005839H

Rotor Resistance: 1.395ohm, Inductance: 0.005839H

Mutual inductance: 0.1722H

Inertia: 0.0131 J(Kg.m^2)

Friction: 0.002985 F (Nm-s)

Pole pair: 2

To create the single phasing condition, three separate single-phase supply has been considered. Phase A is taken as reference and phase sequence is A, B, C. The peak-to-peak voltage is 326.59 V in all the phases. Phase A, B & C has been taken with a phasor difference of 120 degrees from each other to make an equivalent three-phase source.

All the results are performed with conditions mentioned below

Input Supply= 3 units of 1-phase 230 V RMS

Relay rating for fault detection – 600 Amp

No load time – T = 0 to 0.75 sec

Full Load (25 Nm) mounting instant T= 0.75 sec

Fault is created at T=1.5 Sec

Boost convertor duty cycle = 0.45

Fig. 7, 8 & 9 shows the input currents drawn from three-phase supply before and after single phasing for fault in phase C. The transient period in when fault occurs, the transient current in faulty phase is almost thrice the normal current while the other phase currents dips momentarily. Later after single phasing the healthy phase currents are 1.55 (max) times normal current which is accepted.

Fig. 10 & 11 shows the output voltage and current of inverter after filtration acts as input to motor of sample phase out of three phases. Motor is rated at 400V line voltage. At start till the rated current starts flowing the voltage reduces to 2/3 of the DC input. The fault only develops a transient and then stabilises after the same.

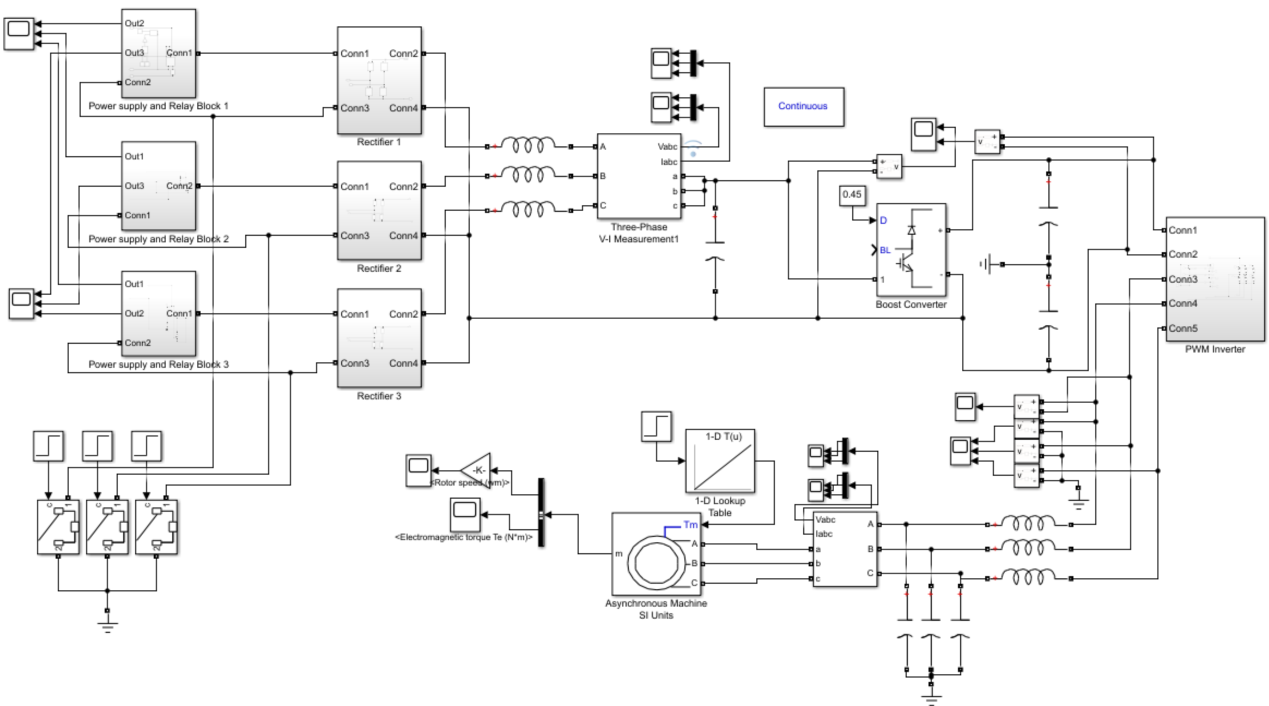

Fig 6. Simulink (MATLAB) model

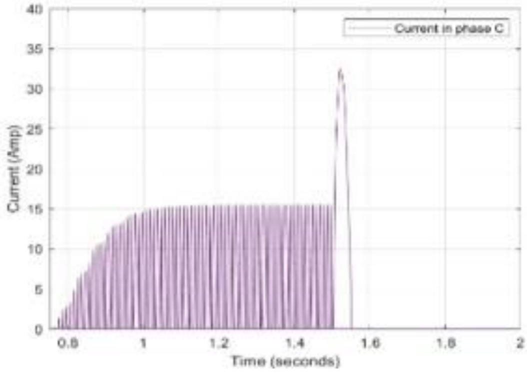

Fig. 7 Phase C current after L-G fault in phase C

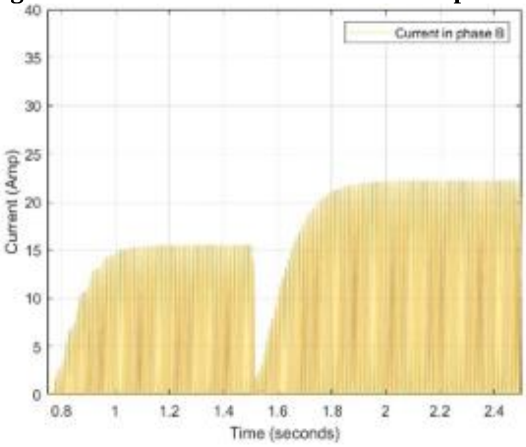

Fig. 8 Phase B current after L-G fault in phase C

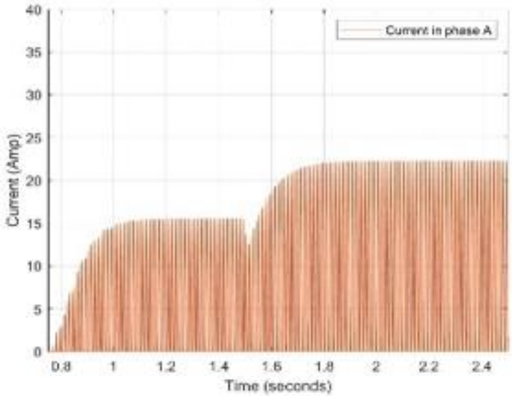

Fig. 9 Phase A current after L-G fault in phase C

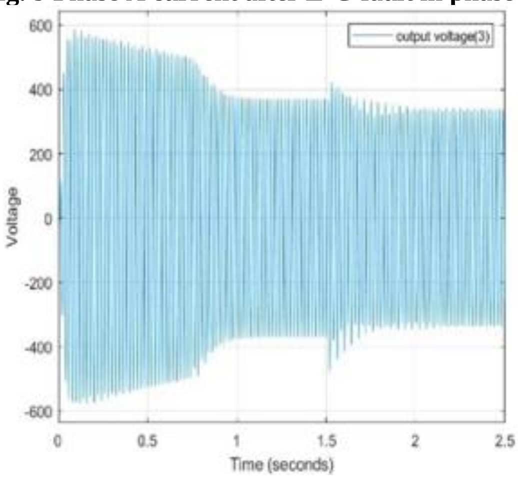

Fig. 10 Inverter output voltage of phase A

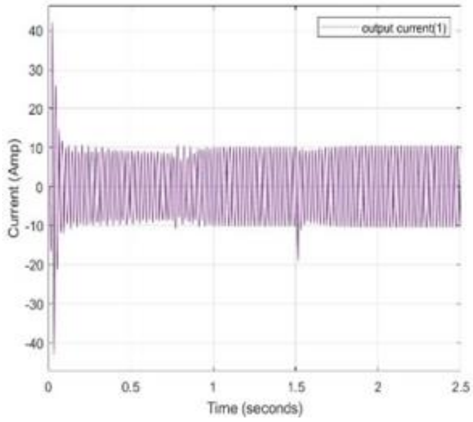

Fig. 11 Inverter output current of phase A

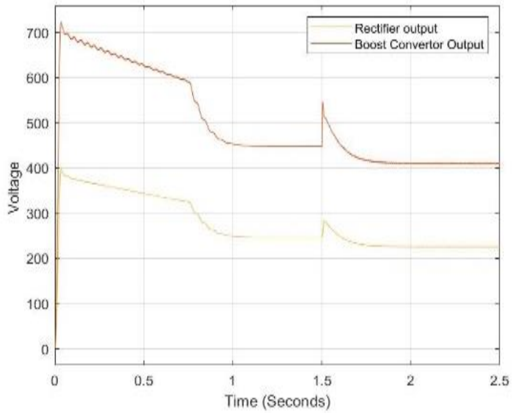

Fig 12. Boost converter and rectifier output voltage

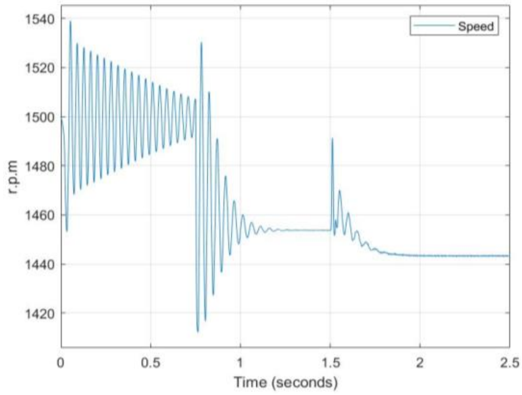

Fig.13 Motor output speed

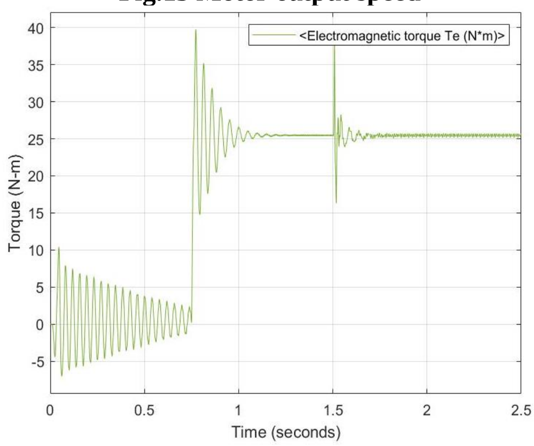

Fig.14 Torque output of motor

Fig 12. Shows output voltage before and after connecting boost convertor. After stabilizing in case of single phasing (after 2 secs approx.) rectifier output voltage is 250 V which to boosted to 450 V.

Figure 13. shows the speed of motor at different time intervals, Speed at no load is 1500 rpm. Speed at healthy running full load condition is 1454 rpm. Speed during single phasing condition comes out to be 1443 rpm

Figure 14. shows torque output of motor. Maximum motor torque is evaluated by

$$Power = \frac{2\pi NT}{60}$$

Putting the known quantities maximum torque comes out to be 26.7 N-m but practically we don't get more than 25 N-m. Motor output torque shown in graph is 25.5 N-m extra 0.5 N-m used to counter friction and inertia or wasted by motor.

VI. CONCLUSION

VFDs are used in industries for continuous operation to improve the overall efficiency. The modified circuit design of VFD under single phasing has been tested in Simulink of MATLAB software under full load condition. The current drawn from the supply end is balanced from the remaining healthy phases under single phasing with the modification in the uncontrolled rectifier circuit. The result shows that by increasing the current rating of the rectifier components the drive could be run at full load speed at rated torque. The protection of the motor can be taken care of by the thermal relays after increasing the fuse ratings of the drive. The fluctuations produced during loading and single phasing are within standard limits and transients die out fast due to small time constant. The MOSFET is preferred over IGBT due to small current rating of the whole system. This work could be further extended to make it more efficient by increasing efficiency of filters. This project is performed only on single type of motor and with fixed rating. There exists a huge scope of practical testing with other types and higher rated motors. If tested on all types of motors this idea can lead to building of a new design of VFD which can run even during single phasing.

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