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SUPPLY INSTABILITY INDUCED TORQUE VARIATIONS OF A THREE PHASE ASYNCHRONOUS MOTOR

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ABSTRACT

The torque profile of a three phase asynchronous or induction motor is an indicator of the load handling capacity of the motor. The torque profile of the asynchronous motor is determined by the motor design and by the nature of the voltage supply. The power supply network in Nigeria is unreliable with frequent supply interruptions and outages daily, due to insufficient power generation and supply capacity. These disturbances and recurrent switching on and off may trigger voltage swings below and above the rated line voltage coupled with the tendency for supply frequency variations. In this study, the torque profile of a typical three phase asynchronous motor running under simulated power supply variations is studied in order to reveal the effects of such fluctuations on the motor. Power supply variations, interruptions and low power quality impair motor performance characteristics and these affects the reliability and operational efficiencies of processes where such motors are installed. The result reveals torque variations from the rated value with changing supply conditions which is undesired for a smooth industrial operation.

Keywords: Frequency perturbations, motor performance characteristics, power quality, power supply variations, three phase induction motor

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1. INTRODUCTION

Power supply availability, reliability and quality are vital indices that determine the efficiency and the productivity of industrial operations [1]. Production lines incorporate several drive systems that are often sensitive to power supply fluctuations and surges. The asynchronous or induction motor is a major equipment in the industries due to its ruggedness, relatively cheap cost and low maintenance requirements [2-5], but the operation of the asynchronous motor can be marred by poor power supply quality [4, 6]. The efficiency, torque profile, temperature and winding losses of the asynchronous motor are influenced by the nature of the power supply. The line voltage of the power distribution network can be affected by the nature and the configuration of the power supply source, and the type of loads connected to it [7, 8].

Energy poverty is a major concern in some African countries, and other low income countries due to inadequate power infrastructure, corruption and poor planning. In Nigeria, in the first four months of 2018 alone, the national grid collapsed at least three times, throwing the whole nation with a population of over 180 million into total blackout. Nigeria currently generates less than 15% of the appraised national energy demands [4, 9], and this is grossly inadequate to support the industrial electrical energy needs. Consequently, companies and households are forced to setup alternative energy sources to support the inadequate public power supply [10]. Diesel and petrol generators are imported heavily into the country, although the influx of these generators help to meet the energy needs to an extent, but the extensive yearly importation creates FOREX deficit and also promotes the generation of greenhouse gases which depletes the ozone layer.

Power supply is unreliable in Nigeria, and in some communities there could be power outage for weeks while others experiences frequent interruptions which triggers supply fluctuations creating power quality issues due to excessive load shedding [9, 11-15], and this creates voltage pulsations, and line voltage variation and supply imbalance which affects the operation of a three phase asynchronous motor [16]. An asychronous motor has a rated voltage and operating frequency as stated on the name plate, by the manufacturers, but often these motors are subjected to supply scenairos that differs from the manufacturers supply specifications. In this study, the influence of supply voltage deviations from the rated voltage and frequency on the operating torque of a three phase asynchronous motor is considered.

The efficiency of an asynchronous motor is affected by the quality of the power supply [7], and this makes it important to understand the impacts of various supply scenarios on the operation of the asynchronous motor, and in particular for the Nigerian power supply situation. Frequent load shedding, excessive alternator start-up and shut down, and excessive circuit breaker trips can trigger voltage swings and line frequency variations. In this study the, the torque of a typical three phase asynchronous motor directly connected to the supply, without using any purpose specific Variable Frequency Drive (VFD) is studied, as the line voltage deviates within ±10% of the rated voltage and ±8% of the rated frequency.

2. THE THREE PHASE ASYNCHRONOUS MOTOR OPERATION USING A VFD

The three phase asynchronous or induction motor shown in Figure 1 generates a magnetic field that runs at the synchronous speed (N_S), while the mechanical speed of the rotor (N_r) is determined by the motor slip (s).

$$N_s = \frac{120 \cdot f_s}{P} \quad \text{(rpm)} \qquad 1$$

$$s = \frac{N_s - N_r}{N_s} \qquad 2$$

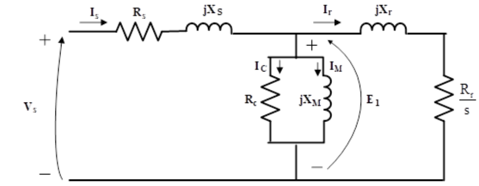

Figure 1 The per phase equivalent circuit of a 3-phase asynchronous motor

Hence, for a fixed pole motor, the speed of the motor is determined by the frequency of the supply and the motor slip. The speed of the motor can be changed by changing the supply frequency, and this is achieved using a variable frequency drive (VFD) [5, 17]. The use of VFD can result in harmonics which causes peaky rotor current leading to increased motor heat [5], and therefore filters are required to remove the injected harmonics. With respect to Figure 1, the induced voltage E is a function of the air gap flux and the slip frequency such that when the supply frequency is reduced, without a corresponding change in supply voltage, there is an increase in the air gap flux, and if the flux increase persists the magnetic circuit will be eventually saturated resulting in increased motor loss, production of high pitch noise, voltage and current waveform distortion [17]. Likewise, if there is a reduction in air gap flux far below the rated flux, the torque capability of the motor will be impaired. To prevent this, when there is a reduction in frequency the phase voltage is also reduced in such a way as to maintain a constant E/f ratio [18], and this is achieved using a VFD that ensures a constant air gap flux. For the air gap flux to be constant, the magnetizing current I_{mag} must be kept constant with varying frequency.

Let $F_1$and E_1 be the rated frequency and voltage, and F_2 and E_2 the new frequency and voltage, such that

$$C_{E/f} = \frac{f_2}{f_1} \quad (3)$$

$$I_{mag1} = \frac{E_1}{X_{m1}} = \frac{E_1}{2\pi f_1 L_m} \quad (4)$$

$$I_{mag2} = \frac{E_2}{X_{m2}} = \frac{E_2}{2\pi f_2 L_m} = \frac{E_2}{2\pi C_{E/f} f_1 L_m} \quad (5)$$

For I_{mag1} to be equal to I_{mag2} then,

$$E_2 = C_{E/f} E_1 \quad (6)$$

When the slip and $C_{E/f}$ are both kept constant, the motor torque and rotor current remains constant for a constant flux control strategy.

3. DIRECT SOURCE CONNECTED THREE PHASE ASYNCHRONOUS MOTOR

In the case of a three phase asynchronous motor that is connected directly to the supply source without a VFD i.e. speed control is not required. When there is a fluctuation in supply frequency due to supply network instability and poor power quality issues, the motor will respond to this frequency change and the torque regime of the motor will vary in accordance with the supply disruptions.

With reference to Figure 1, the impedance of the magnetizing circuit is defined as

$$Z = R_c \,//\, jX_m = \frac{jR_c X_m}{R_c + jX_m} \quad (7)$$

The overall motor impedance is obtained as follows

$$Z_m = R_s + jX_s + \frac{Z \times (jX_r + \frac{R_r}{s})}{Z + jX_r + \frac{R_r}{s}} \qquad 8$$

The stator current for the three phases is given by

$$\begin{pmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{pmatrix} = \begin{pmatrix} \frac{1}{Z_m} & 0 & 0 \\ 0 & \frac{1}{Z_m} & 0 \\ 0 & 0 & \frac{1}{Z_m} \end{pmatrix} \begin{pmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{pmatrix} \qquad 9$$

Let $Z_z = \frac{Z_m}{Z + jX_r + \frac{R_r}{s}}$ 10

The rotor current for the three phases is given by

$$\begin{pmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \end{pmatrix} = \begin{pmatrix} Z_z & 0 & 0 \\ 0 & Z_z & 0 \\ 0 & 0 & Z_z \end{pmatrix} \begin{pmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{pmatrix} \qquad 11$$

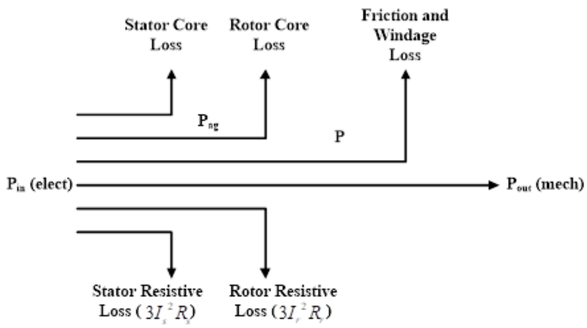

Figure 2 The Power flow diagram [19]

The power supplied to the motor is transferred from one stage to the other with associated losses before it is finally available as the useful mechanical shaft power; this is summarized in Figure 2.

Given the developed mechanical power, the rotational losses (windage and friction) and other stray losses, the output power can be obtained from

$$P_{out} = P_{dev} - P_{rot} - P_{stray} \qquad 12$$

The developed or induced torque of the machine is the torque generated due to the conversion of electric power to mechanical power, and it is defined as:

$$T_{dev} = \frac{Airgap\ power}{Synchronous\ speed(rad/\sec)} \qquad 13$$

4. MAXIMUM TORQUE VARIATION

To determine the maximum torque as the voltage supply swings above and below the rated balanced voltage (BV), the Thevenin equivalent of the induction motor model shall be applied. By applying Thevenin's theorem to the per-phase stator circuit of Figure 1, the following analysis is developed

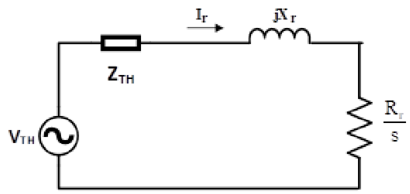

Figure 3 Thevenin equivalent of a 3-phase induction motor

$$Z_{TH} = Z // (R_s + jX_s) = \frac{Z(R_s + jX_s)}{Z + R_s + jX_s} \qquad 14$$

$$Z_{TH} = R_{TH} + jX_{TH} \qquad 15$$

$$V_{TH} = \frac{Z}{Z + R_s + jX_s} \times V_s \qquad 16$$

$$I_r = \frac{V_{TH}}{\left(R_{TH} + \frac{R_r}{s}\right) + j\left(X_{TH} + X_r\right)} \qquad 17$$

$$Torque\ (T) = \frac{3I_r^2 R_r}{s\omega_s} \qquad 18$$

$$T = \frac{3V_{TH}^2 R_r}{s\omega_s\left(R_{TH} + \frac{R_r}{s}\right)^2 + s\omega_s\left(X_{TH} + X_r\right)^2} \qquad 19$$

The starting torque is defined by equation (20)

$$T_{start} = \frac{3V_{TH}^2 R_r}{\omega_s\left(R_{TH} + R_r\right)^2 + \omega_s\left(X_{TH} + X_r\right)^2} \qquad 20$$

The maximum torque and the maximum air gap power occur at the same slip; this can be determined using the maximum power transfer theorem.

$$Airgap\ Power = \frac{3I_r^2 R_r}{s} \qquad 21$$

$$P_{air} = \frac{3V_{TH}^2 R_r}{s\left(\left(R_{TH} + \frac{R_r}{s}\right)^2 + \left(X_{TH} + X_r\right)^2\right)} \qquad 22$$

$$P_{air} = \frac{3V_{TH}^2 R_r}{sR_{Th}^2 + 2R_{TH}R_r + \frac{R_r^2}{s} + sX_{Th}^2 + 2sX_{TH}X_r + sX_r^2} \quad 23$$

$$\frac{\delta P_{air}}{\delta s} = \frac{0 - 3V_{TH}^2 R_r \left[R_{Th}^2 - \frac{R_r^2}{s^2} + X_{Th}^2 + 2X_{TH}X_r + X_r^2 \right]}{\left[sR_{Th}^2 + 2R_{TH}R_r + \frac{R_r^2}{s} + sX_{Th}^2 + 2sX_{TH}X_r + sX_r^2 \right]^2} \quad 24$$

At the maximum point $\frac{\delta P_{air}}{\delta s} = 0$ 25

$$0 = R_{Th}^2 - \frac{R_r^2}{s^2} + X_{Th}^2 + 2X_{TH}X_r + X_r^2 \quad 26$$

$$\frac{R_r^2}{s^2} = R_{Th}^2 + \left(X_{TH} + X_r \right)^2 \quad 27$$

The slip at maximum torque

$$S_{\max} = \frac{R_r}{\sqrt{R_{Th}^2 + \left(X_{TH} + X_r \right)^2}} \quad 28$$

5. THE SIMULATION RESULT AND ANALYSIS

A simulation of the voltage and frequency supply fluctuation scenario was carried out using MATLAB. A voltage variation of ±10% of the rated balanced three phase voltage (BV) was applied, while the following frequencies were considered: 46Hz, 48Hz, 50Hz, 52Hz, and 54Hz, as the slip increased from 0 to 0.08. The three phase asynchronous motor for this analysis has the following parameters: 415V, Xm = 26.1Ω, Xs = 0.748Ω, Xr = 0.72Ω, Rr = 0.736Ω, Rs = 0.464Ω, Rc = 682Ω, constant losses = 118W. The result of the simulation is shown by the charts of figure 4 to figure 17, and Table 1.

Table 1 Motor performance at the rated voltage (415V), rated frequency (50Hz) and rated slip (0.046)

PARAMETER	0.9BV	0.95BV	BV	1.05BV	1.1BV
Total Loss (W)	987.22	1,086.47	1,191.11	1,301.10	1,416.46
Shaft Power (W)	7,259.18	8,101.64	8,989.63	9,923.16	10,902.23
Input Power (W)	8,246.39	9,188.11	10,180.73	11,224.26	12,318.69
Reactive Power (VAR)	5,632.80	6,276.06	6,954.08	7,666.87	8,414.43
Apparent Power (VA)	9,986.57	11,127.01	12,329.09	13,592.83	14,918.20
Efficiency (%)	88.03	88.18	88.30	88.41	88.50
Power Factor	0.8257	0.8257	0.8257	0.8257	0.8257
Starting Torque (Nm)	176.52	196.68	217.93	240.27	263.69
Torque (s=0.046) (Nm)	49.23	54.85	60.78	67.01	73.54
Max Torque (Nm)	214.04	238.49	264.25	291.34	319.74

The motor losses at the rated frequency are plotted in Figures 4 to 6. The rotor winding copper loss at the rated slip (0.046) and rated frequency (50Hz) is 355.71W at 0.9BV, 396.33W at 0.95BV, 439.15W at the balanced rated voltage, 484.17W at 1.05BV and 531.37W at 1.1BV, while the stator winding copper loss is 331.71W at 0.9BV, 369.60W at 0.95BV, 409.53W at BV, 451.51W at 1.05Bv and 495.53W at 1.1BV. The total losses which includes the winding losses, the core loss and the constant losses is 987.2W at 0.9BV, 1086.5W at 0.95BV, 1191.1W at BV, 1301.1W at 1.05BV, and 1416.5W at 1.1BV. The motor losses increase with increasing voltage due to the increasing rotor currents. The motor losses also increase as the slip increases, and this cumulative energy losses produces heat which increases the motor temperature [20]. The variation of the motor shaft power for all the voltage scenarios with respect to the rated voltage, at the rated frequency and slip is plotted in Figure 7.

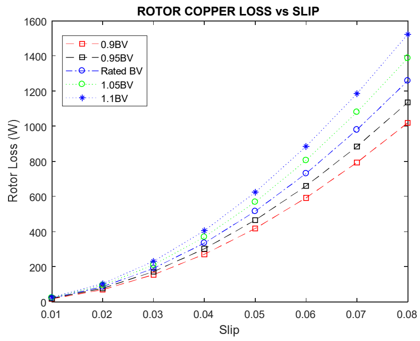

Figure 4 The rotor winding loss at the rated frequency

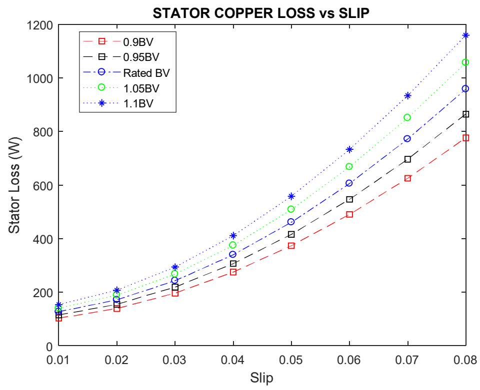

Figure 5 The stator winding loss at the rated frequency

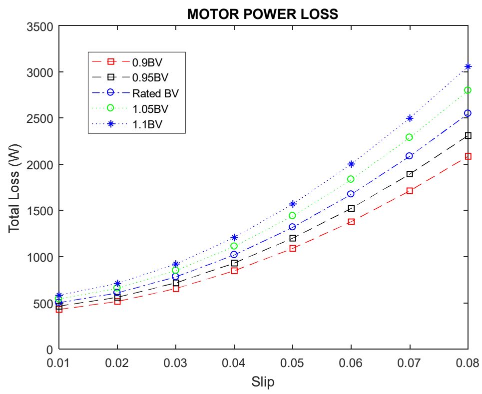

Figure 6 The total motor loss at the rated frequency

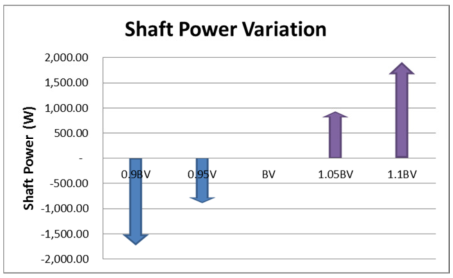

Figure 7 Shaft power variation at the rated frequency and slip

The data in Table 1 contains relevant information on the motor operational performance. As the input voltage is increased from 0.9BV to 1.1BV, the input power also increased from 8,246.39W to 12,318.69W that is 66.94% increase. The reactive power increased from 5,632.9VAR to 8,414.43VAR, and this ultimately culminated in an increased apparent power from 9,986.57VA to 14,918.20VA. Supply instability causes the motor power consumption to vary with line fluctuations and this also resulted in torque pulsations as the breakdown torque increased from 214.04Nm to 319.74Nm.

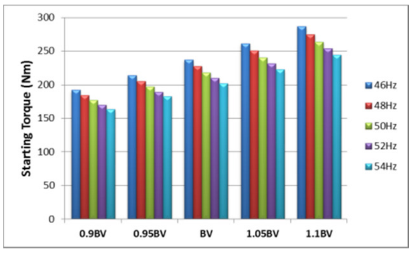

Figure 8 The motor starting torque profile at different frequencies and voltages

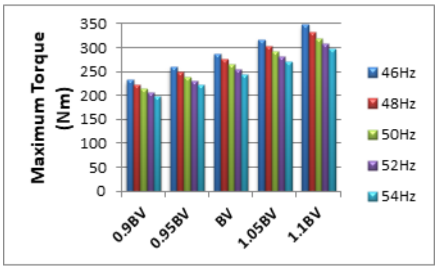

Figure 9 The motor breakdown torque profile at different frequencies and voltages

The starting torque and the breakdown or maximum torque at the different frequencies and line voltages are plotted in Figure 8 and Figure 9. The chart reveals an increment in the motor torque with increasing line voltage, while there is a reduction in torque with increasing supply frequency. The torque profile at specific supply frequencies, with increasing slip and line voltage are plotted in figures 10 to 14. These charts further confirms the increment in torque with increasing voltage, and it also shows a significant increase in motor torque as the slip increased from 0.01 to 0.08. The torque profiles of the motor for the different frequencies, voltage and slip are summarized in Figure 15. From Figure 15, it can be clearly observed that as the supply frequency increased from 46Hz to 54Hz, the output torque of the motor reduced accordingly while the motor speed increased from 1380 rpm to 1620 rpm. All these unintentional motor performance fluctuations due to supply instability are not desired in processes where the motor is deployed, and as such this may affect the process reliability and the operational efficiency of such systems especially in manufacturing companies where production line speed and production rate are pre-programmed. The torque pulsations may also result in mechanical faults and bearing damage.

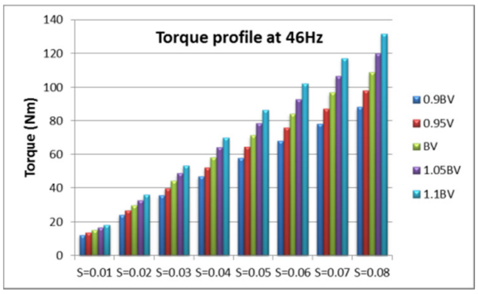

Figure 10 The motor torque profile at 46Hz

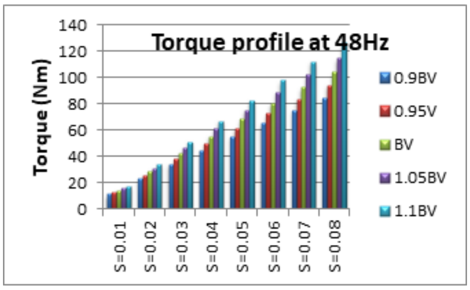

Figure 11 The motor torque profile at 48Hz

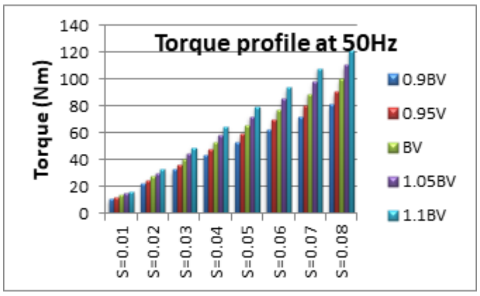

Figure 12 The motor torque profile at rated frequency of 50Hz

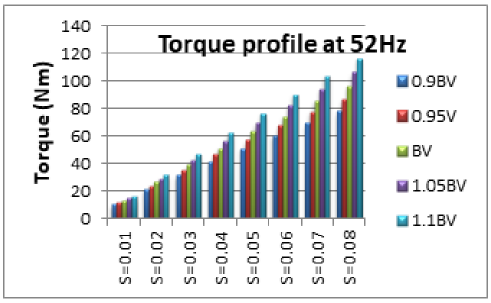

Figure 13 The motor torque profile at 52Hz

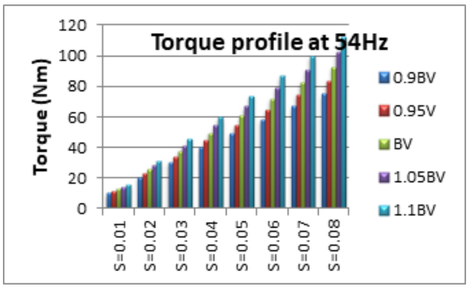

Figure 14 The motor torque profile at 54Hz

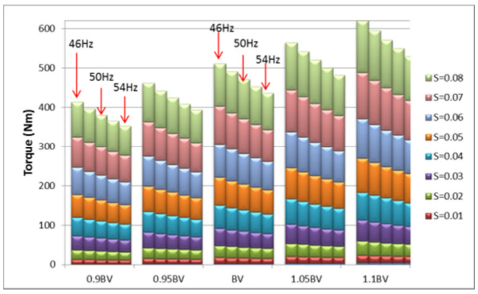

Figure 15 A summary chart of the motor torque profile

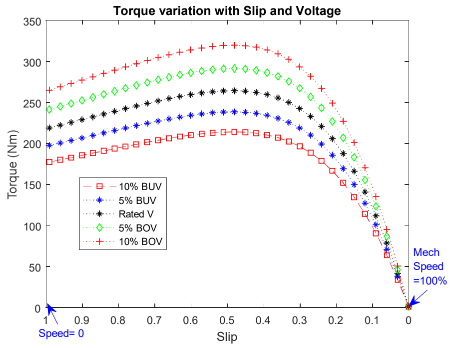

Figure 16 The torque profile within the motoring range at the rated frequency (50Hz)

Figure 16 shows the torque profile across the full motoring slip range, showing the starting torque when the rotor mechanical speed is zero till the speed attains the synchronous speed when the slip becomes zero. The breakdown torque increased with increasing line voltage, if the supply voltage continues to increase, thereby driving the motor torque above the breakdown torque, the motor may be destroyed, and likewise if the load exceeds the breakdown torque the motor will stall.

As shown in Figure 17, at -1 < slip < 0 the motor operates in the generating mode [21], and between slip = 0 and slip = 1, it works as a motor, while at slip > 1 the motor operates in the plugging mode in which the mechanical speed is negative. The implication of this is that the shaft power becomes zero and goes negative as the machine is no longer motoring, but the air gap power remains positive, which implies that power is flowing from the stator to the rotor, and also from the mechanical system into the rotor. This is typically applied in motor breaking, and the rotor current must be reduced to a safe value in order to limit high transient torque and prevent motor damage [22].

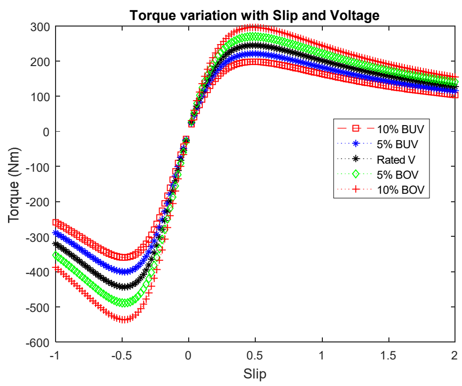

Figure 17 The motor torque profile across a slip range of -1 to 2 at f =50Hz

6. CONCLUSION

Power quality is a vital determinant of the performance of asynchronous motor, and as such, poor power quality may militate against the operational benefits of the motor, especially for industrial purposes. In this study, the consequences of the power supply challenges, low reliability, and the instability of the Nigerian power supply network on the torque profile of a typical three phase asynchronous induction motor is analysed and presented. The study reveals that for motor applications where speed control through VFD is not desired, and the motor is directly connected to the supply source, the effects of line voltage variations and frequency perturbations, are transmitted directly to the motor. This causes the motor torque to vary in accordance with these supply fluctuations, thereby affecting the load and other associated processes. Line voltage variations below the motor torque hinders the motor load capability while voltage variations above the rated motor voltage results in an increased motor loss which is dissipated as heat, and this increases the operating temperature of the motor which may reduce the motor life span on the long run.

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