Inverter Coupled Energy Storage System for Soft-Restarting of Power System Dynamic Load

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Abstract: - This paper presents the design and implementation of an inverter-coupled energy storage system (ESS) for the soft-restarting of dynamic loads in power systems, utilizing MATLAB Simulink as the simulation platform. The proposed system aims to enhance the reliability and stability of power grids by providing a controlled and efficient method for restarting loads after an interruption. The inverter-coupled ESS integrates a battery storage unit with a power inverter to supply the necessary energy for a smooth load restart, minimizing the impact on the overall system. Simulation results demonstrate the effectiveness of the system in maintaining voltage stability, reducing inrush currents, and ensuring a seamless transition during the load restarting process. The study highlights the potential of inverter-coupled ESS in modern power systems, offering a robust solution for managing dynamic load behavior and improving grid resilience.

Key-Words: - Inverter-Coupled Energy Storage System, Soft-Restarting, Power System Stability, Dynamic Load, MATLAB Simulink, Voltage Stability, Inrush Currents, Battery Storage, Grid Resilience, Power Inverter, Load Management, Power Grid Reliability

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1. Introduction

Industrial processes like producing goods or manufacturing any product can suffer major loss in financial means due to the interruption of power cut. These processes get encountered and get completed with the help of motors which are of ratings from 0.5 to 500 hp in which 30%-35% are line connected. In 2012, Federation of Indian Chambers of Commerce & Industry (FICCI) revealed that firms generally do not suffer any shortfall in production due to the erratic power supply. This is because the firms have adapted themselves to the current power scenario so well that all that they suffer is cost escalation due to the use of power backups to support their production activity. However, it was considered important to ask the industrial groups about any shortfall that they might incur due to the intermittent power supply, in case they do not use power backups to support their operations, the regarding results are shown in figure 1 [1]. The main objective of the study is to understand the impact of power outages on the Indian industry. An analysis of the shortfall or impact on production due to power cuts is thus paramount. Generally in Indian industries, there are several firms which are being converted to independent power suppliers since they require continuous power supply to get desired output within stipulated time to fulfil the customer's requirement. But it is not so reliable to consider due to occurrence of certain mishaps which would not be predictable

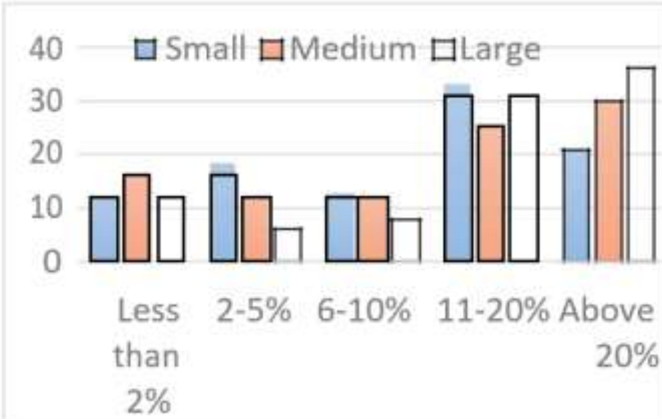

Figure 1. Distribution of shortfall in production due to outages by type of enterprises

The graph mentioned in figure 1 shows that due to power outages, there is significant increase in the shortfall of production of industrial grades which get noticed over not using alternate power supply [2]. Also system transients are also responsible for the highest number of failures of electronic components [3].

The energy-storage systems (ESSs) can be alternative as an auxiliary source for industrial plant is reported in studies [4]-[6]. Some heavy industries such as Pulp and Paper (80-300 MW) commonly generate a fraction (20%) of their own energy onsite [7]. In this paper, we use ramping power which is supplied from a local energy-storage system (ESS) inverter. This power is fed to the industrial power system bus and then ensures a transient-free load transfer to the grid source. This method is termed as 'Soft-Restarting' which is initiated after an occurrence of three-phase-to-ground fault which is external to the load zone supplied by ESS. There are certain benefits of soft-restarting (SR) method which are as follows:

1. Automatic and continuous process.
2. No process downtime so no any external handling (labour operation) requires to restore the system hence labour cost get reduced.
3. Method ensures predefined inrush currents.
4. Line equipment like distribution transformer can be downsized or their maintenance can be delayed.
5. Unsuccessful reclosing attempts get avoided after the occurrence of faults or momentary interruptions.
6. Synchronization is achieved by the inverter to perform a transient-free load transfer to the grid source.

2. Proposed System

In this section, the generalized view of the system and circuit breakers operating sequence is discussed for better understanding of the system.

2.1 Generalized View of the System

The system which is proposed in this paper is as shown in figure 2, which includes an industrial load connected to the industrial bus i.e. load-bus as named in the figure 1. As stated earlier, industrial loads varies from o.5 hp to 500 hp motors, so here the use of an asynchronous motor of rated power 400 hp has been done which is considered as an industrial load. To drive the load bus, bus is getting supply from grid source and at fault condition bus gets disconnected due to the operation of circuit breakers: circuit breaker 1 (CB_1), circuit breaker 2 (CB_2) and main circuit breaker (CB_main). The sequence of operation of circuit breakers plays vital role in maintaining proper condition of the network [8]. Mainly we are dealt with the circuit breaker and relay operation to carry out the effectiveness of the soft-restarting method. Simpler way to carry out this process is to understand the circuit breakers operation thoroughly and to use it in simulation. Which is described preceding to this as below.

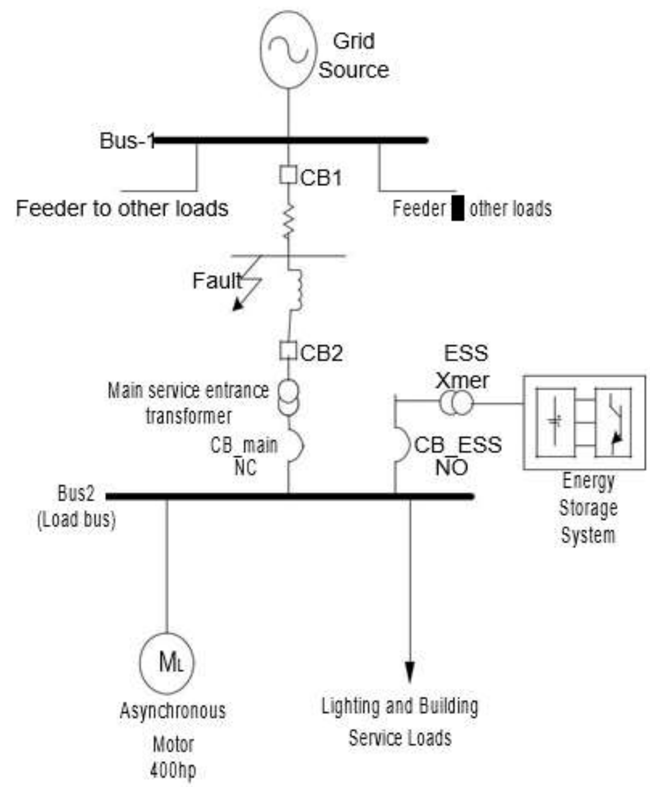

Figure 2. A small representative of an industrial power network with line connected asynchronous motor

2.2 Circuit Breaker's Operating Sequence

In this system, we are considering a fault occurrence which is a three-phase-to-ground fault in somewhere between circuit breaker-1 and circuit breaker-2. This fault is considered as much severe as compared to other types of fault. Such fault can harm or damage a system permanently [9]. Several circuit breakers are used for the purpose of protection of system or any equipment depending on their requirement and parameters [10]. Following operations takes place during s oft-restarting process.

1. A three-phase-to-ground fault takes place in between CB_1 and CB_2.
2. Following this fault, CB_1-CB_2 and CB_main get tripped in response to overcurrent and undervoltage relay respectively.
3. While the system gets isolated from the load bus, then inverter-coupled ESS starts supplying the power by closing its circuit breaker which is normally open. ESS then supply the ramp power to the load bus until the voltage and frequency ratio (V/Hz) get matched to the grid source supply. This situation is called as ramp-up process in which inverter supply ramping power to the load bus.
4. As soon as voltage and frequency get matched, inverter stops supplying the power and load get transferred to the grid source by reclosing the CB_main and tripping off circuit breaker of energy storage system (CB_ESS).

There are certain conventional practices which are used for the reclosing of the motors after fault conditions. These conventional practices are harmful since there is certain amount of residual voltage present in the motors which would be dangerous for system restoration [11]-[12]. To avoid a possible cascaded voltage collapse that may result from this effect, the system must quickly be restored to normal condition [13]. Hence by using soft-restarting method, one can avoid such hazards since in soft-restarting, the loads get transferred to the utility without any transients.

3. Inverter-Coupled Energy Storge System Contol

In this proposed system, we are using an three -phase three-level diode clamped inverter to supply ramp power to the load bus for achieving synchronization with the system. Actually, the generation of ramp-power is not so easy. It requires certain control variables for the operation of synchronous reference-frame phase locked loop (SRF-PLL) and for maintaining the V/Hz ramp control. SRF-PLL related with ramp control is shown in figure 3.

As shown in figure 3, the current feedback is only used to adjust the V/Hz ramp. An open loop V/Hz supply is generated by the ESS inverter to power up Bus-2 (Load Bus). The control variables are obtained by abc-to-dq transformation. Vq and Ꮚline are derived from SRF-PLL [14] and are used as inputs to the Vq-Controller and frequency-controller respectively. But before these we have to derive the positive sequence componet of the voltage which is used to fed at the abc -to-dq transformation. This positive sequence of the voltage can be derived with the help of sequence analyzer [15]-[16].

Here we are not using Vd to adjust the magnitude and frequency of the V/Hz ramp, so it is set to zero. As Vd_inv = 0, hence the inverter output voltage magnitude is:

$$|V_{inv}| = V_{q\_inv}$$

abc-to-dq transformation also known as Park's Transformation [17], which gives line voltages which have been detected as positive sequence voltages into dq variables as:

$$V_{q\_line} = \sqrt{2}\, V_{abc\_line} COS[(\omega_{line} - \omega_{inv})t + \theta_{line0} - \theta_{inv0} + \delta] \quad (2)$$

$$V_{d\_line} = \sqrt{2}\, V_{abc\_line} \sin[(\omega_{line} - \omega_{inv})t + \theta_{line0} - \theta_{inv0} + \delta] \quad (3)$$

Where,
Vabc_line = (rms) magnitude of line-to-neutral voltage at load bus;
Ꮚline = detected line frequency
Ꮚinv = detected inverter output frequency

ϴline and ϴinv0 = phase angle constant. We select time zero such that ϴline = 0 and ϴinv0 = 0

δ is the voltage angle between Vabc_line and Vinv with phase angle of 0 degree referred to the ESS bus or load bus. We are not using d-axis voltage as a control variable for inverter, hence we will use only equation for further analysis. The phase angle δ is derived from the transformer coupling impedance RT
+ jXT. The frequency controller block is used to control the detected line frequency is as shown in figure 5. In which output Vq from abc-to-dq transformation is fed to the controller block, from which we are getting theta (ϴ). ϴ is being used as a control variable for the inverter and is given to the inverter as an input.

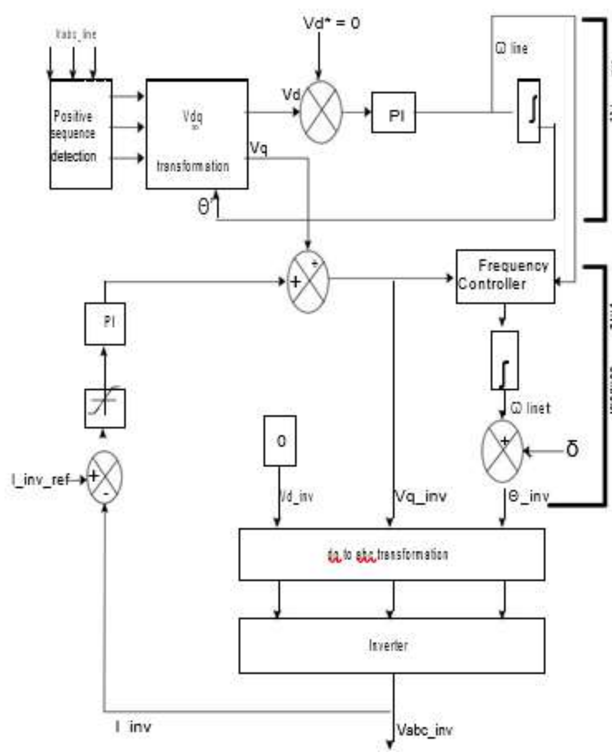

Figure 3. Control schematic of inverter-coupled ESS

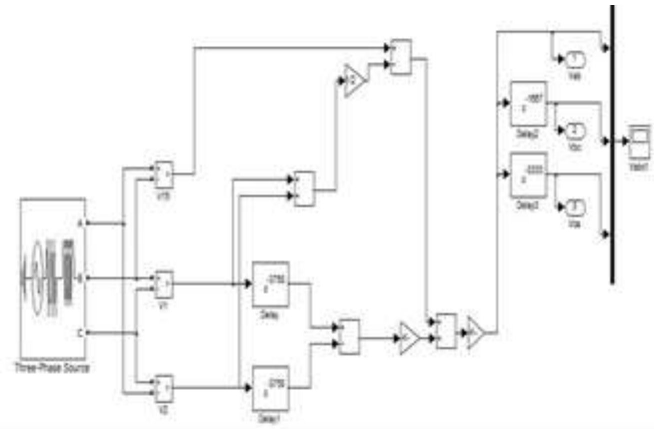

Figure 4. Positive sequence analyzer

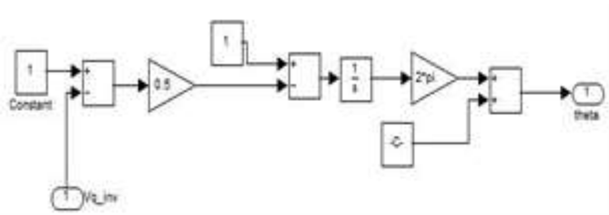

Figure 5. Frequency controller

4. Operation During Ramp (V/Hz) Control

The decaying voltage and frequency at time of fault condition, given by Vq0 and f0 respectively, have a non-linear relationship that will highly depend on the inertia of the motor load connected to the load bus. The operation during ramp control in which Vq at time t i.e Vq(t) is simply get controlled by PI controller as shown in figure 6.

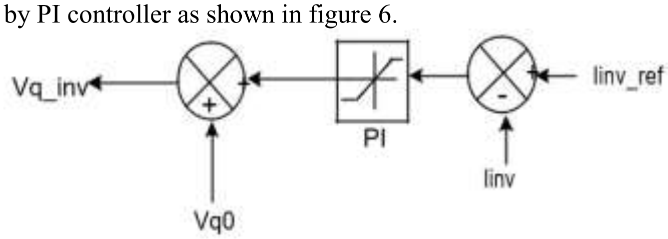

Figure 6. Vq controller

Therefore Vq(t) is defined as:

$$V_q(t) = V_{qinv}(t) = V_{q0} + m_{Vq}t \qquad (4)$$

for t = any time in between the operation of ramp control when inverter supplying ramp power. mvq is slope of the voltage ramp and it is controlled by PI controller.

$$f_{inv}(t) = 1 - \pi \frac{1}{K_0}\left(1 - V_{qinv}(t)\right) \qquad (5)$$

Where, t = any time in between the operation of ramp control and f_{inv} = rated inverter output frequency

$$K_0 = \frac{1-V_{q0}}{1-f_0} \qquad (6)$$

Equation (5) is used to determine frequency of the inverter which is then used to determine the angle input (Ɵinv) to the inverter from:

$$\omega t_{line} = 2\pi \int f_{inv}(t)dt \qquad (7)$$

5. Simulation Parameters and Results

An industrial optimized asynchronous motor is considered as a load which is driven by load torque given to the shaft and it is expressed [18] as:

$$T_L = [T_{init} + (T_F - T_{init})\omega^2] \times T_B \qquad (8)$$

where,

T_{init} = initial load torque during startup

T_F = final load torque

ω = motor speed in rad/sec

T_B = base torque in N-m

Table 1: Parameters For Asynchronous Motor

Prated (hp)	400
VLrated	480
f (Hz)	50
N (rpm)	1470
J (kg-m²)	0.089
F(N.m.s.)	0.0065
Rs (Ω)	0.435
Rr (Ω)	0.816
Lls (H)	0.00016
Llr (H)	0.00019
Lm (H)	0.6931

Table II. Transformer Parameters

Rated Power	1.2 MVA
Voltage Rating	2000V/480V, Y-Y
Impedance	4+j3.4%

Table III. Parameters For Ess

Battery Voltage	1.2 MVA
Inverter Switching	500

Frequency	

5.1. During Normal Restarting

At fault condition, CB1, CB2 and CB_main get tripped. According to the characteristics of their respective fault clearance timing, each of them clear the fault with respect to overcurrent and undervoltage of the system condition. So at normal restarting of the system, it requires much timing for system restoration and for transferring the load to the utility. Hence during normal restarting of the system, corresponding voltage and current results are as shown for the proposed system which is simulated using MATLAB/SIMULINK.

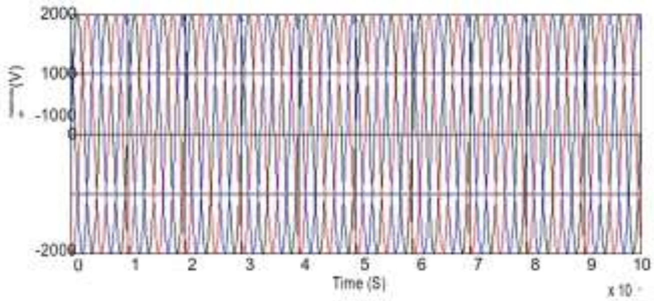

Figure 7. Rated voltage

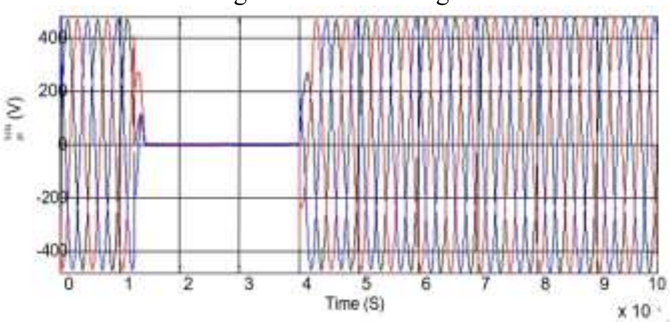

Figure 8. Output voltage at load bus during normal restarting

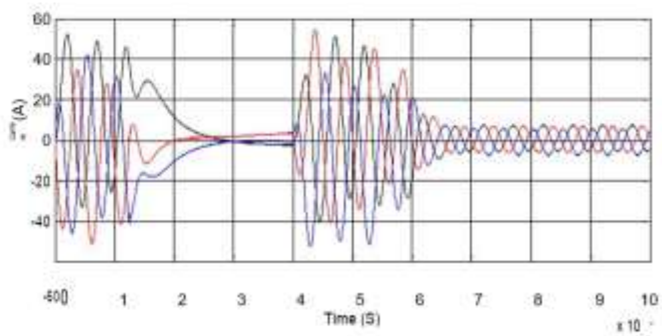

Figure 9. Output current at load bus during normal restarting

5.2. During Soft-Restarting

The output results for soft-restarting method is as shown below, in which the time required for the system to close and to transfer the load to the utility get reduced, hence better and fast service restoration is achieved. Also for the current output, the transients which were noticed even after the normal restarting of the system get overcome and time required is also less as compared to normal restarting method.

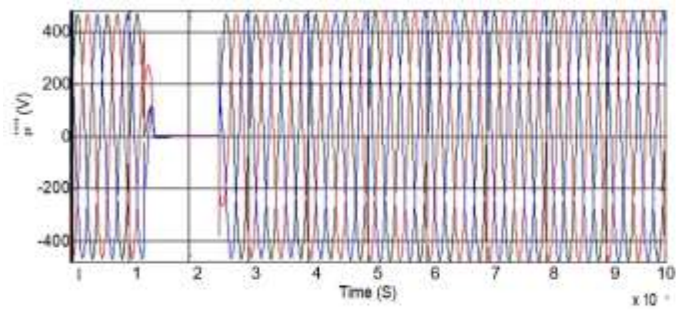

Figure 10. Output voltage at load bus during soft-restarting

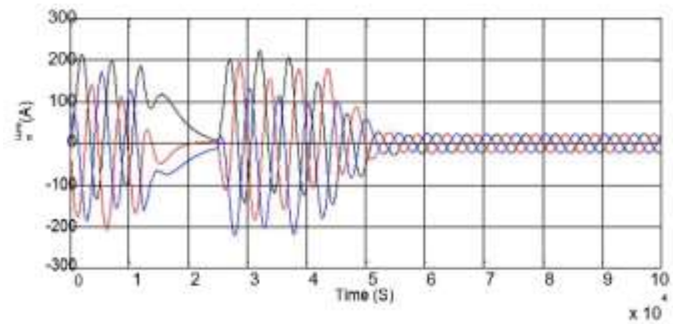

Figure 11. Output current at load bus during soft -restarting

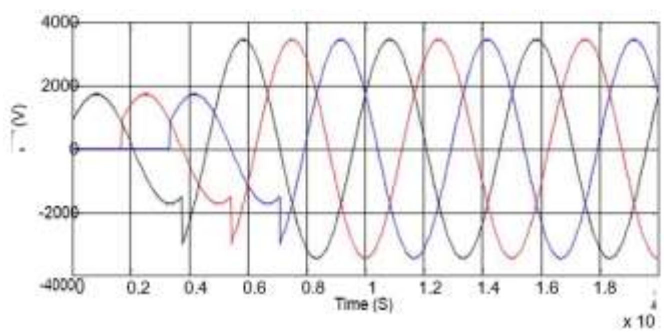

Figure 12. Output Positive sequence voltage

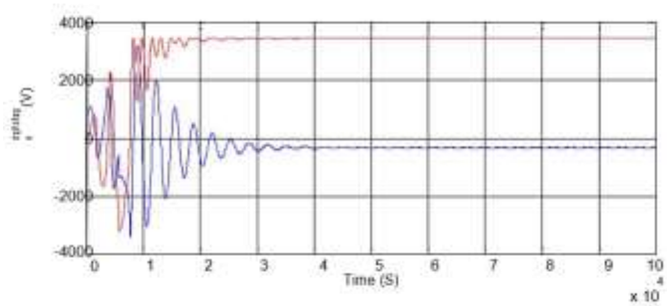

Figure 13. Output voltage from abc to dq transformation

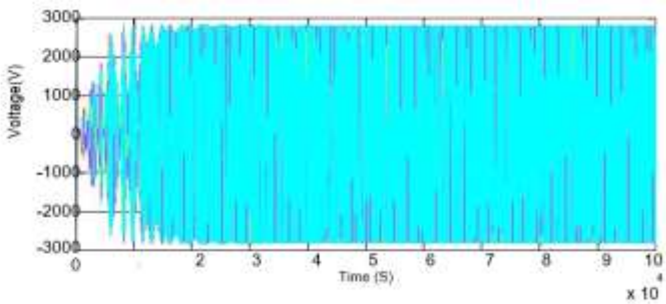

Figure 14. Inverter output voltage

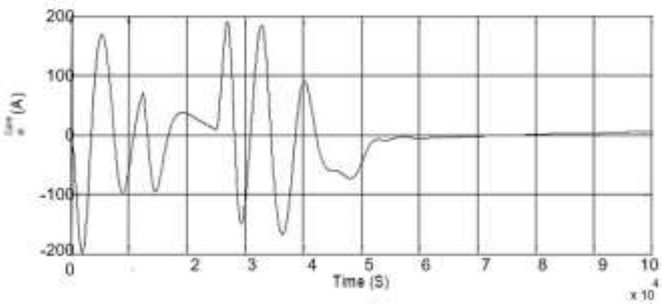

Figure 15. Output rotor current

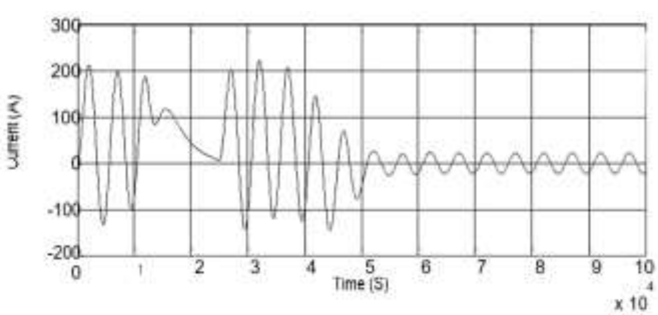

Figure 16. Output stator current

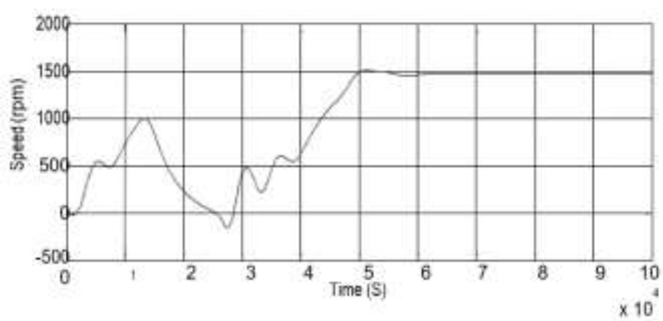

Figure 17. Motor speed

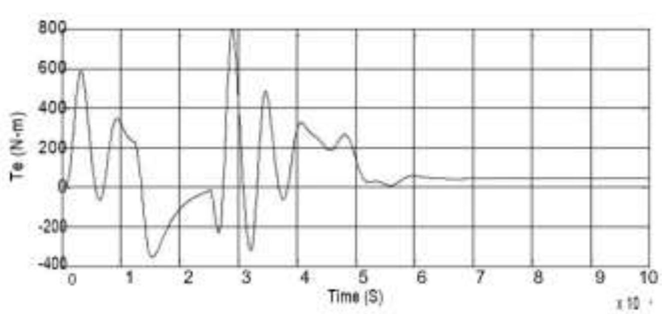

Figure 18. Electromagnetic torque output

6. Conclusion

For transient-free load transfer in industrial power network, a system is proposed in this paper. The res ults are simulation based which are obtained for the proposed system parameters. The current transient during normal restarting and during soft restarting has been compared, by which we come across the fine results of soft-restarting in which current trans ients are get reduced and the time required for the system restoration is also get reduced. Hence this method is reliable in case of industrial loads for acquiring service restoration after fault as quick as possible.

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