International Journal of Advances in Electrical Engineering

E-ISSN: 2708-4582
P-ISSN: 2708-4574
IJAEE 2025; 65(1): 01-25

www.electricaltechjournal.com
Received: 05-12-2024
Accepted: 02-01-2025

Dr. Abdulsatar H Jasim
Assistant Professor,
Department of Electrical,
College of Engineering,
University of Tikrit, Iraq

Marwa emad Mohamed
Department of Electrical,
College of Engineering,
University of Tikrit, Iraq

Correspondence
Dr. Abdulsatar H Jasim
Assistant Professor,
Department of Electrical,
College of Engineering,
University of Tikrit, Iraq

Three-phase synchronous motor performance under and over unbalanced voltage

Abdulsatar H Jasim and Marwa emad Mohamed

Abstract
The synchronous machine is an AC machine that maintains its speed regardless of the load (Within normal bounds) and the (Stable) operating regime. The relationship between the machine's rotor's rotation speed and the rotating magnetic field defines the synchronous machine's operational characteristic. A three-phase synchronous motor is designed to operate under balanced three-phase supplies, while A three-phase supply can become unbalanced due to operational realities such as uneven line current switching, imbalanced transformer windings, unequal single-phase loads on each of the three phases of the supply, etc. This study examines the detrimental effects of unbalanced voltage of 450 W three phase synchronous motor salient-pole rotors in case unity, and leading power factor with load.

Keywords: Synchronous machine, AC machine, rotating magnetic field, synchronous motor

1. Introduction
Numerous studies on synchronous motors have been published by numerous specialists. jyx.jyu.fi - A Zaretskiy -Jyväskylä, 2013 focuses on examining the oscillations and stability of three-phase synchronous machines with a four-pole rotor at different feed system connections (Parallel and series) [1]. C Jäger, I Grinbaum, J Smajic, 2017 Comprehensive simulation techniques for synchronous machine dynamic analysis are offered. The accuracy of 2-D and 3-D transient electromagnetic simulations is specifically examined by contrasting them with measurements that have been made on a testing salient pole synchronous machine (SM) in three-phase, two-phase, and single-phase short-circuit (SC) scenarios [2]. C. CRISTEA and I. STROE, 2017 provides information about the synchronous motor's electrical and mechanical features. It is possible to load with varying capacities and experience torsional vibrations by modeling resistive torque and the features of the synchronous motor are displayed over a range of torque values at a steady speed up until the point of step failure [3]. Faria Bernardes and Bortoni, 2020 explains how to restore the machine's characteristics even in the event that the unexpected short-circuit test exhibits high amplitude field voltage variations. Furthermore, a proposed algorithm can define the maximum field voltage variations and the corresponding period to ensure that a specific parameter estimate error is respected. Ultimately, data from a 140 MVA synchronous machine is used to examine the models that have been constructed [4]. Y Ma, L Zhou, J Wang, 2020 demonstrates how to estimate the rotor position parameter arbitrarily for standstill time-domain response (SSTR) testing. The method is applied to a 300 MVar, 20 kV big synchronous condenser, with the input signal being a DC step voltage signal. First, it is shown how to employ a frequency-domain Dalton-Cameron transformation to concurrently acquire operating inductances for both axes in any rotor position, so doing away with the requirement for rotor prepositioning. And after that, a new analytical parameter [5]. D Aguilar, F Ferreira, A De Almeida, M Cistelecan, 2022 discussed beginning torque, part- and full-load efficiency, and synchronization. Furthermore, the mains voltage's magnitude deviation and/or imbalance, which significantly impair starting Line-start permanent magnet synchronous motors' torque and synchronous speed (LSPMSM) with special focus on the steady-state performance of the motor and the consequences of magnitude variation and voltage imbalance [6]. AA Kebir, M Ayad, S Kamel, 2022 examine the impacts of harmonic pollution and voltage imbalance on the five-phase permanent magnet synchronous machine using spectrum current analysis and wavelet transform [7]. Elsevier, 2023 offers a methodical approach to determining the values of synchronous machine parameters and the associated

circuit. The scope of the study is expanded to examine the performance characteristics of the machines and the behavior of three-phase synchronous machines under either dynamic or steady-state settings. Plotting the phasor diagram and the V-curves that show how changing field excitation affects the synchronous motor with a fixed load, with a fixed field excitation, it shows how changes in load affect the synchronous motor. In addition, the relation between torque, excitation, and current is investigated [8].

2. Modeling of Synchronous Motor in d-q Frames

The rotor reference frame, also referred to as the "d − q reference frame," serves as the foundation for the current modeling framework for synchronous motor. Through the use of various mathematical transformations like Park's transformation, the stator values (Such as voltages, currents, and flux connections) are transformed in the rotor reference frame and vice versa [9] where it is computationally challenging to solve the phase quantities directly using the stator self and mutual inductances as well as the stator-rotor mutual inductances. The inverse of the time-varying inductance matrix must be calculated at each time step in order to extract the phase currents from the flux connections. This takes time and could lead to issues with numerical stability to compute the inverse at each time step. So, A d-q rotating reference frame is used to convert stator quantities in order to eliminate time-varying values in flux linkages, phase inductances, voltages, and currents. As a consequence, time-invariant coefficients appear in the machine equations [10]. According to conventional theory, the armature, dampers, and field on direct-axis windings have identical mutual inductances when modeling a synchronous machine for stability analysis. Since damper windings are often close to the air gap, the flux linking damper circuits is nearly equivalent to the flux linking armature. This theory yields results that are appropriate for a variety of stability investigations, particularly those of network-side. But there is a significant error when it comes to field current investigations. Measurements of field current in transient and sub-transient modes have occasionally revealed larger alternating amplitudes. Only the armature circuit is accurately described by the traditional two-axis model. The difference between the field-damper and field-armature mutual inductances on the D-axis must be represented by an extra inductance. This inductance, also known as the Canay inductance, is regarded as a correction element in the equivalent model and corresponds to the leakage flux ΦC. It may even acquire a negative value [11].

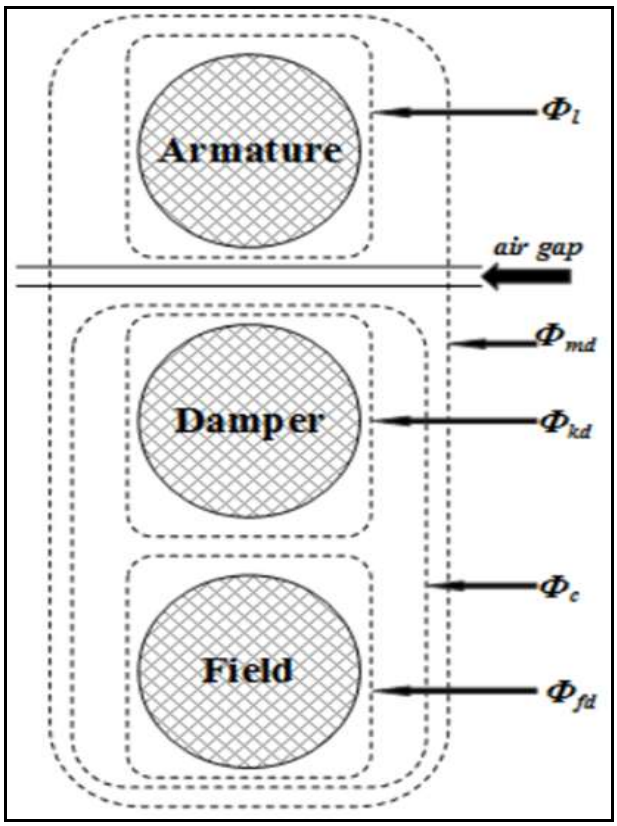


Fig 1: Mutual and leakage fluxes on d-axis

The presumptions that are used in order to create the synchronous motor dynamic models are as follows:

1. The values of inductances do not change with the saturation state.
2. Mutual inductances are neglected.
3. Losses resulting from eddy currents in the core and damping coil are negligible.

Stator, field, and damper winding dynamics are all taken into consideration by the model. The internal neutral point of the stator windings is connected in a wye. Primed variables identify all of the rotor's electrical properties, which are visible from the stator. Seven equations are used to represent the electrical components in the voltage model and mechanical components of the motor. The equations for the models originate from the d-q circuit shown in Figure 2.

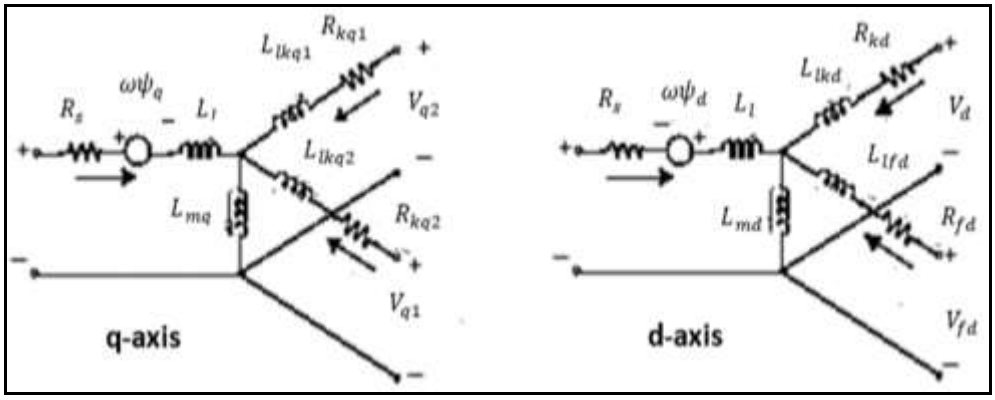
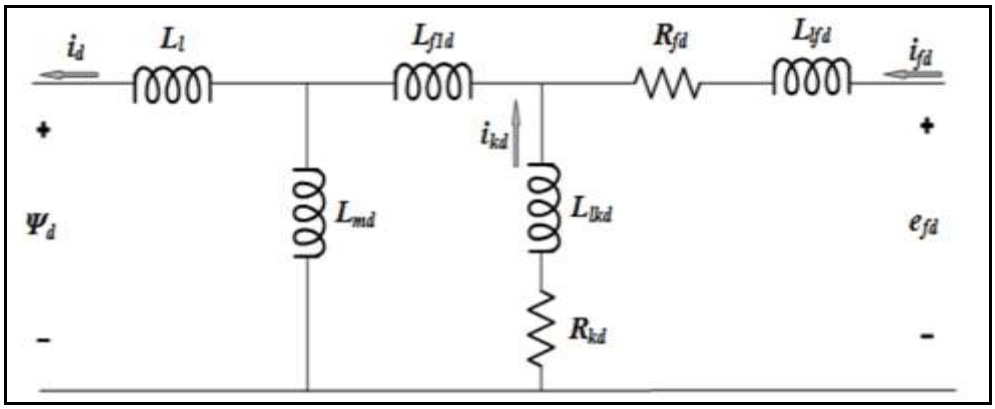


Fig 2: The dynamic model of synchronous machines with direct and quadratic axes

$V_d = -i_d R_s - \omega phi_d + \frac{d\omega_d}{dt}$	1
$V_q = -i_q R_s + \omega phi_q + \frac{d\omega_q}{dt}$	2
$V_0 = -i_0 R_0 + \frac{d\omega_0}{dt}$	3
$V_{fd} = \frac{d\omega_{fd}}{dt} + i_{fd} R_{fd}$	4
$0 = \frac{d\omega_{kd}}{dt} + i_{kd} R_{kd}$	5
$0 = \frac{d\omega_{kq1}}{dt} + i_{kq1} R_{kq1}$	6
$0 = \frac{d\omega_{kq2}}{dt} + i_{kq2} R_{kq2}$	7

And from Figure 3 the relationship between current and flux can be expressed as

$\begin{bmatrix} phi_d \\ phi_{kd} \\ phi_{fd} \end{bmatrix} = \begin{bmatrix} L_l + L_{md} & L_{md} & L_{md} \\ L_{md} & L_{lkd} + L_{fld} + L_{md} & L_{fld} + L_{md} \\ L_{md} & L_{fld} + L_{md} & L_{lfd} + L_{lfd} + L_{md} \end{bmatrix} \begin{bmatrix} -i_d \\ i_{kd} \\ i_{fd} \end{bmatrix}$	8
$\begin{bmatrix} phi_q \\ phi_{kq1} \\ phi_{kq2} \end{bmatrix} = \begin{bmatrix} L_{mq} + L_l & L_{mq} & L_{mq} \\ L_{mq} & L_{mq} + L_{kq1} & L_{mq} \\ L_{mq} & L_{mq} & L_{mq} + L_{kq2} \end{bmatrix} \begin{bmatrix} -i_q \\ i_{kq1} \\ i_{kq2} \end{bmatrix}$	9



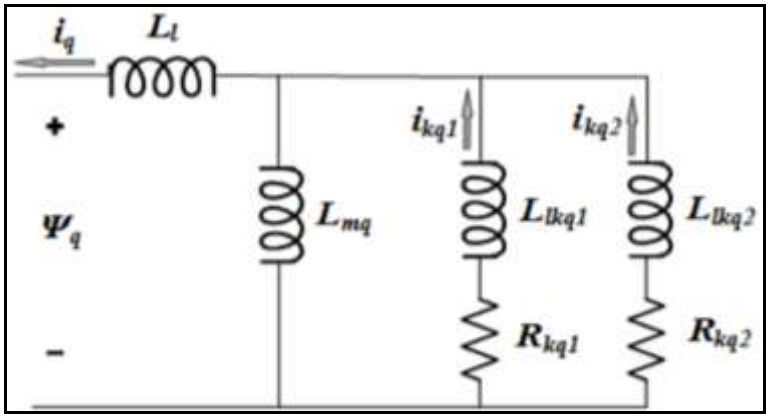


Fig 3: d-q Axis equivalent circuit to illustrate ψ–i relationship

3. Simulink for Three Phase Synchronous Motor

The simulation developed with MATLAB features a dynamic creating a synchronous motor model. in this modeling, there are certain sub models included. The electrical sub model transforms the three-phase electrical parameters into the as previously shown reference frames of the two axes, d-q. The torque sub-model computes the electromagnetic torque produced, whereas the mechanical sub model computes the rotor's speed. To calculate the falls in line voltages, a sub model of stator currents output is also supplied. The MATLAB/Simulink for three phase Synchronous Motor as shown in Figure 5.

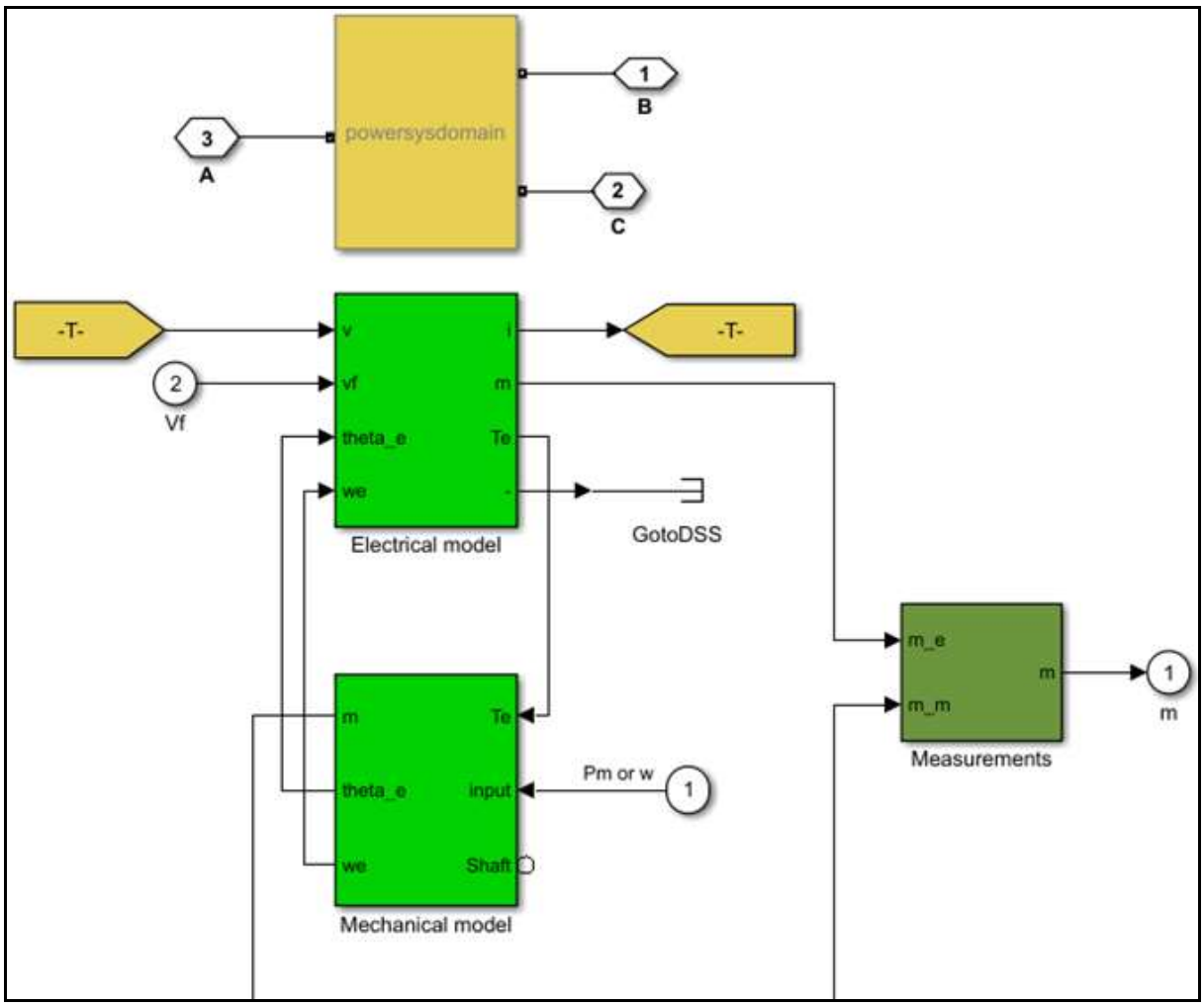


Fig 4: MATLAB /SIMULINK for Three phase Synchronous Motor

3.1 Sub-Model of Electrical Part of Motor

This conversion, also referred to as the "park transformation," is frequently utilized in three-phase electric machine models. Where the analysis and control of three-phase technologies, including machines and inverters, heavily relies on transformations between revolving dq0 reference-frames, stationary dq0 (αβ0), and abc reference-frames [12]. By converting the stator quantities to a fixed, rotating reference frame, this transformation makes it possible to eliminate time-varying inductance. One can see the blocks for the electric sub-model in Figure 6

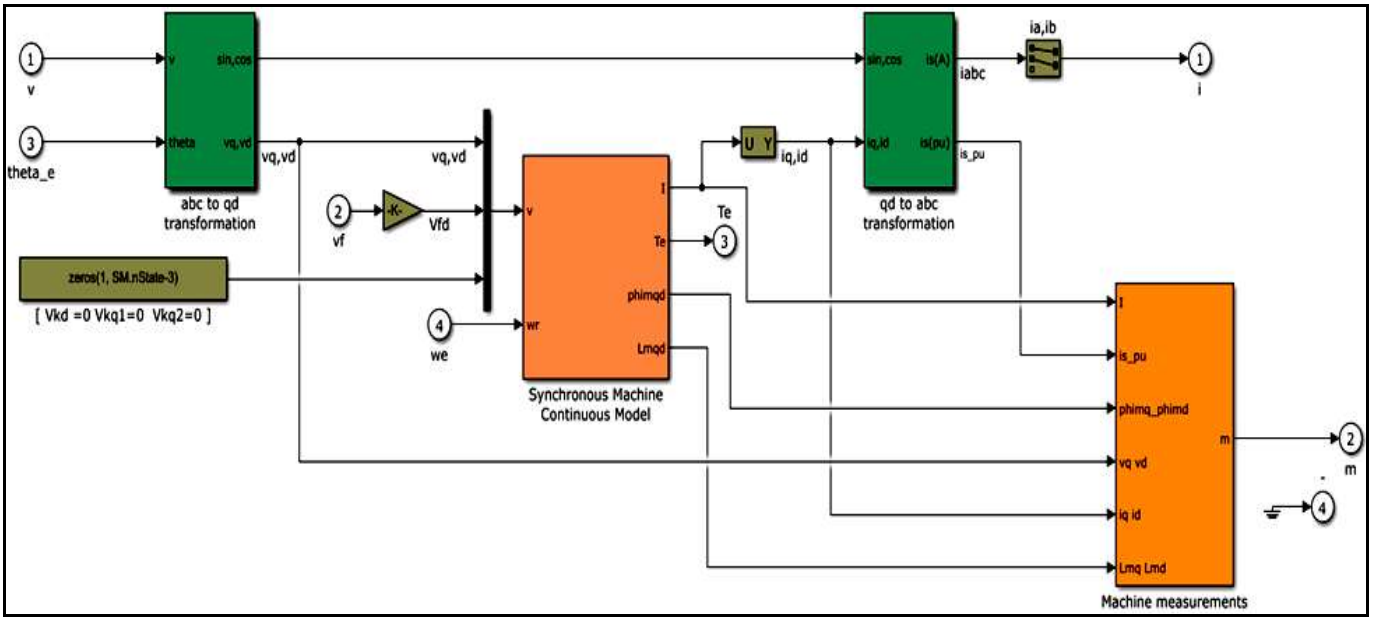


Fig 5: Electrical Sub-Model of Synchronous Motor

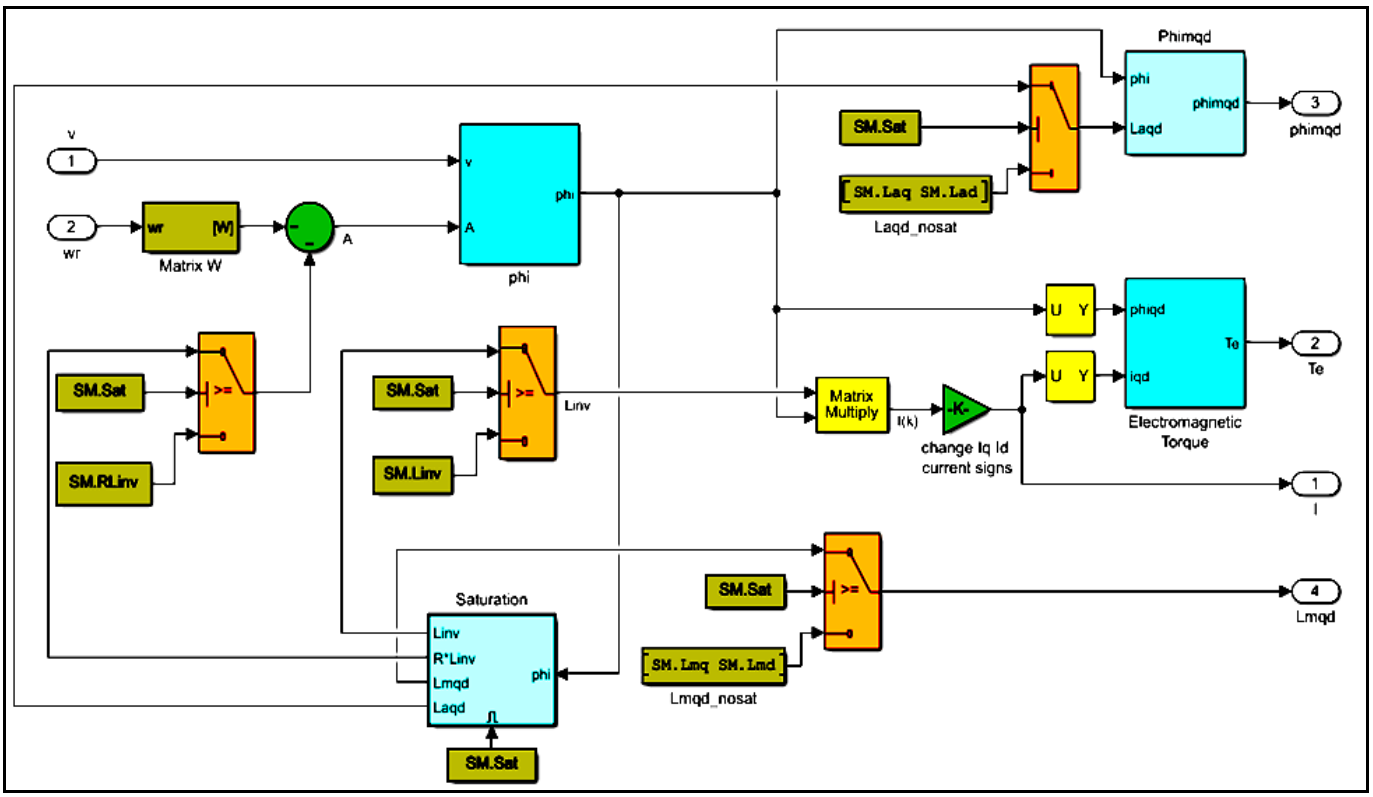


Fig 6: Synchronous Motor Continuous Model

Apply machine equations in the frame of the rotor:

$V = [R] * i + dphi/dt + [w] * phi$	11
$phi = [L] * i$	12

Where:

$[R]$= diagonal matrix (nstate, nstate) of winding resistance in d q axis.

$[L]$= matrix (nstate, nstate) of winding self and mutual inductances in d q axis.

$[w]$= matrix (nstate, nstate) depending on rotor speed w_r.

All zeros except $w(1,2) = w_r$ and $w(2,1) = -w_r$.

V=voltage vector=$[V_q \quad V_d \quad V_{fd} \quad V_{kd} \quad V_{kq1} \quad V_{kq2}]$.
phi= flux linkage vector=$[phi_q \quad phi_d \quad phi_{fd} \quad phi_{kd} \quad phi_{kq1} \quad phi_{kq2}]$(statet faraibale).
i=current vector=$[i_q \quad i_d \quad i_{fd} \quad i_{kd} \quad i_{kq1} \quad i_{kq2}]$.
If rotor type=salient pole, nstatet=5
If rotor type=round, nstate=6
The synchronous reference frame's transition matrix, which employs two element blocks, has been employed in simulation. As shown in Figure 8

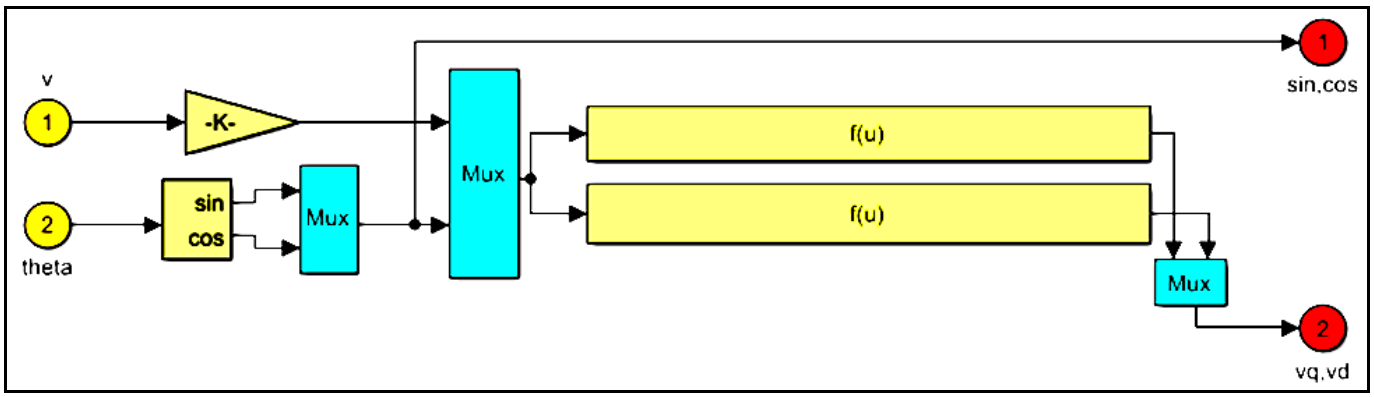


Fig 7: Sub-Model of Transformation from abc to dq

In this subsystem, $V_{ab}$and V_{bc}have been transformed to $V_d$and V_q.This computation of sine and cosine is forwarded to the inverse transformation subsystem dq⁄abc.

3.2 Sub-Model of Torque

The converted currents are then utilized to calculate the induced electromagnetic torque (T_e) as soon as the electrical factors are obtained in the d-q reference frame during the electrical sub-model through the

$T_e = phi_{ds} * i_q - phi_{qs} * i_d$	13

Figure 9 shows the Simulation block for the mathematical analysis necessary for the computation (T_e).

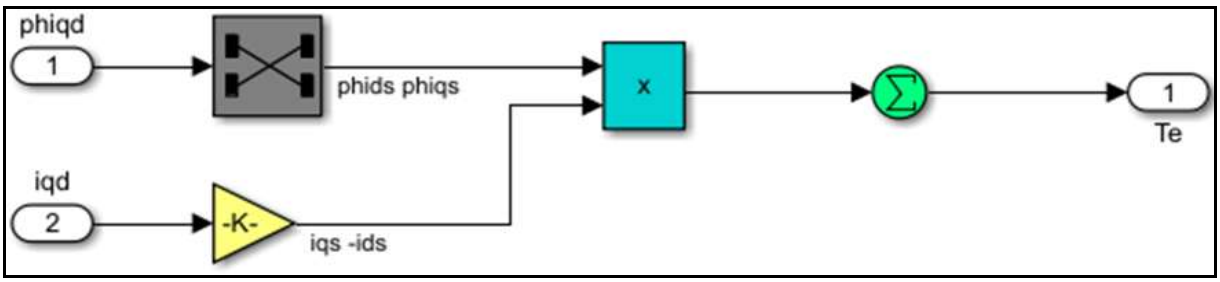


Fig 8: Sub-Model of Electromagnetic Torque

4. Simulation Influences of Voltage Unbalance on 3-ϕ Synchronous Motor

MATLAB/SIMULINK was used to implement the effects of several voltage imbalances throughout this research on the stator current, reactive power, power factor, and efficiency of a 3-ϕ synchronous motor at 87.8 watt in case unity power factor and 70 watt in case leading power factor. As

Table 1: Parameters of synchronous motor

Specifications	Unite	Value	Specifications	Unite	Value
Rated power	KW	350	stator current	A	0.7
Rated voltage	V	400/240	stator resistance	Ω	17
Speed	R.P.M	3000	excitation resistance	Ω	400
Excitation voltage	V	220	Synchronous reactance	Ω	384.359
Excitation current	A	0.45	Direct reactance	Ω	49.4
Pole	_	2	Quadrature reactance	Ω	35.94
Connection	_	Y	Frequency	HZ	50

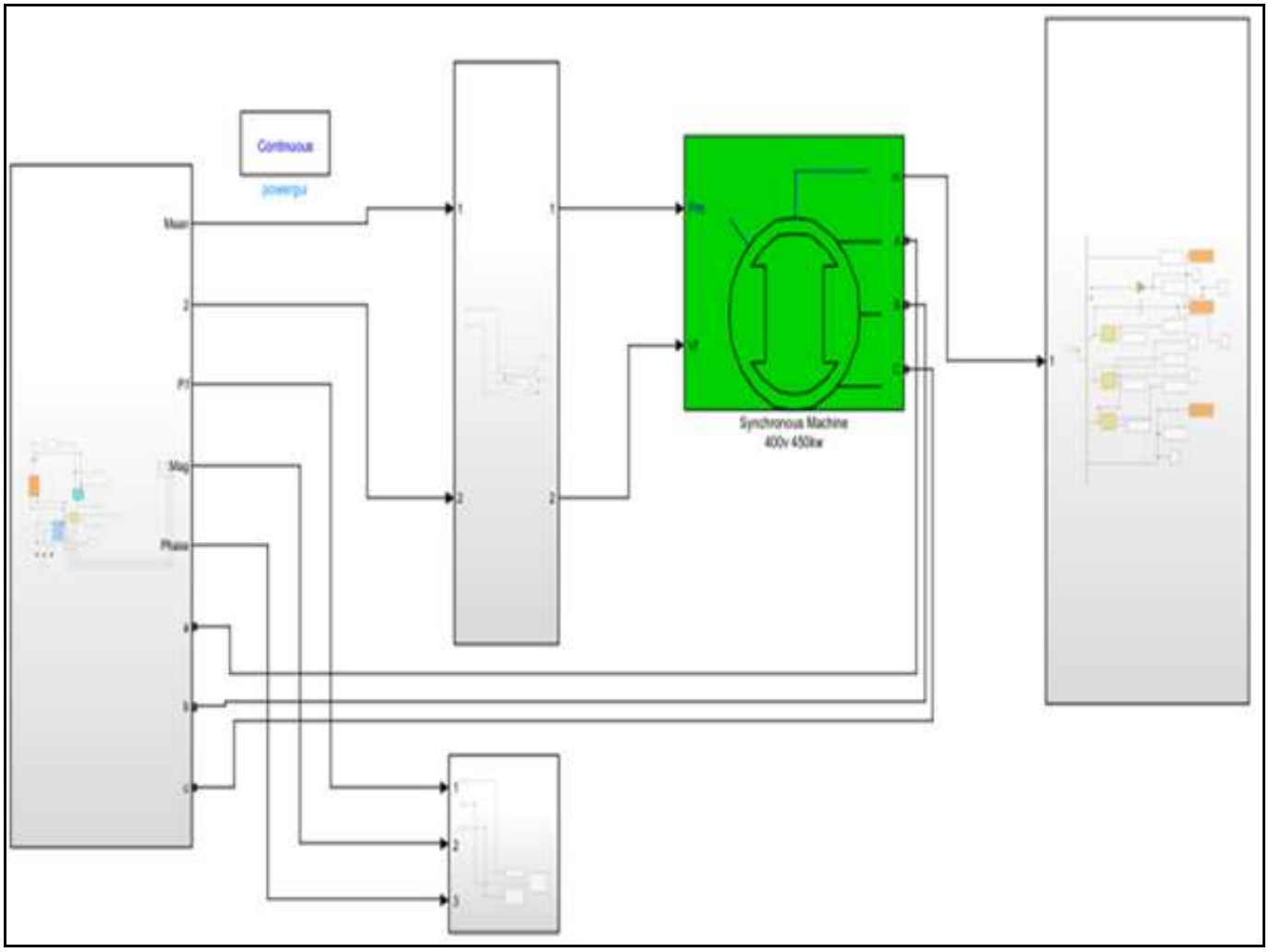


Fig 9: Matlap/Simulink for three-phase synchronous motors powered by sinusoidal voltage that is either balanced or unbalanced

Table 2: Performance of Synchronous Motor at Balance Conditions

	Unity power Factor	**Leading power Factor**
$I_{sa}(A)$	$0.2157\angle -149.4$	$0.2815\angle -116.1$
I_{sb}(A)	$0.2157\angle 91.59$	$0.2815\angle 123.9$
I_{sc}(A)	$0.2157\angle -29.41$	$0.2815\angle 3.911$
$I_{exc}(A)$	0.3175	0.425
$P_{in}(w)$	182.3	200
$Q_{in}(var)$	-1.539	-117.9
$P_{out}(w)$	87.8	70
$T(N*m)$	0.2896	0.2654
$Eff.$	0.4817	0.35
$P.f$	0.999	0.85
Speed (rpm)	3000	3000

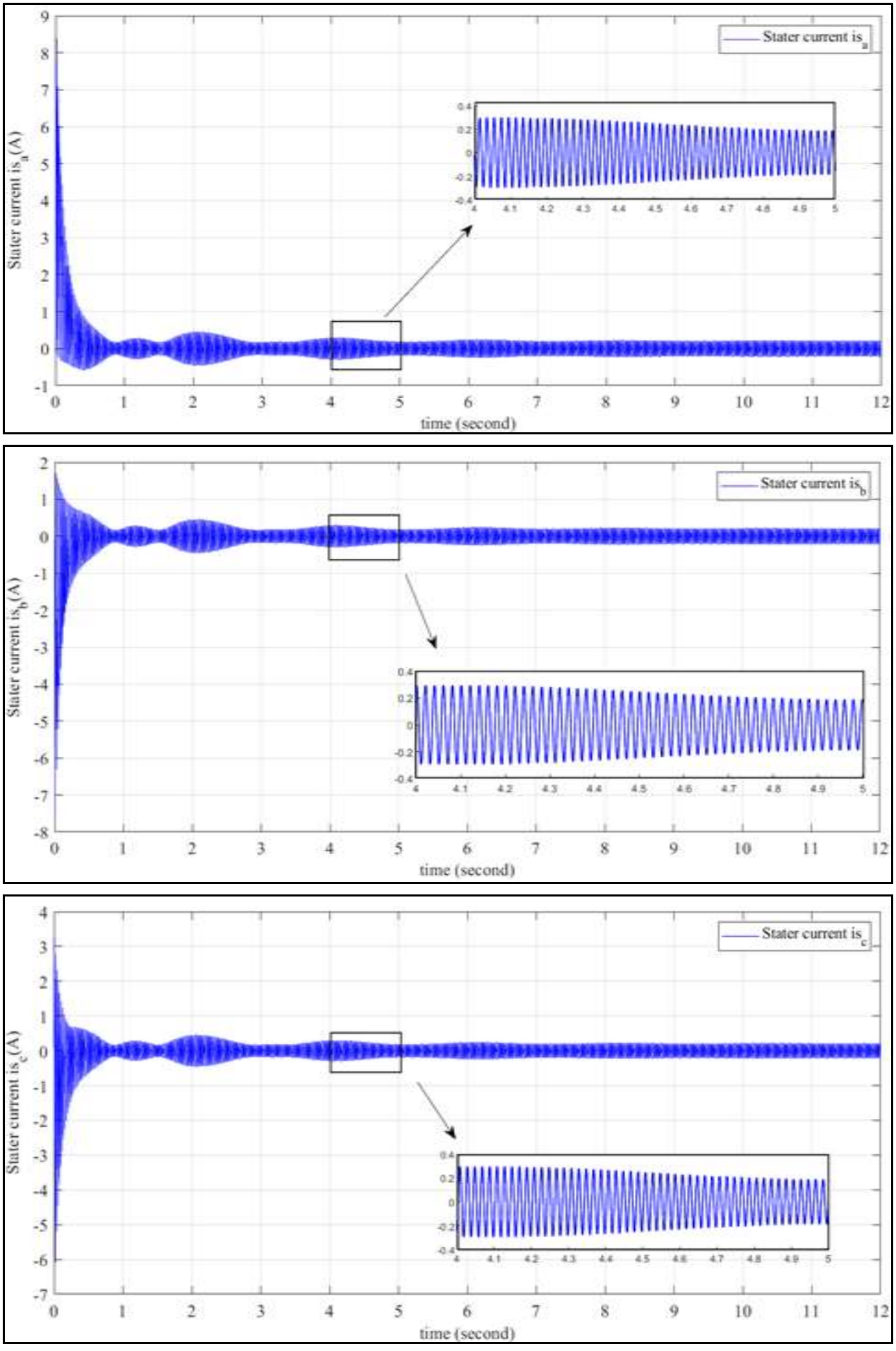


Fig 10: Stater Current for Load Unity Power Factor at Balance Supply Case

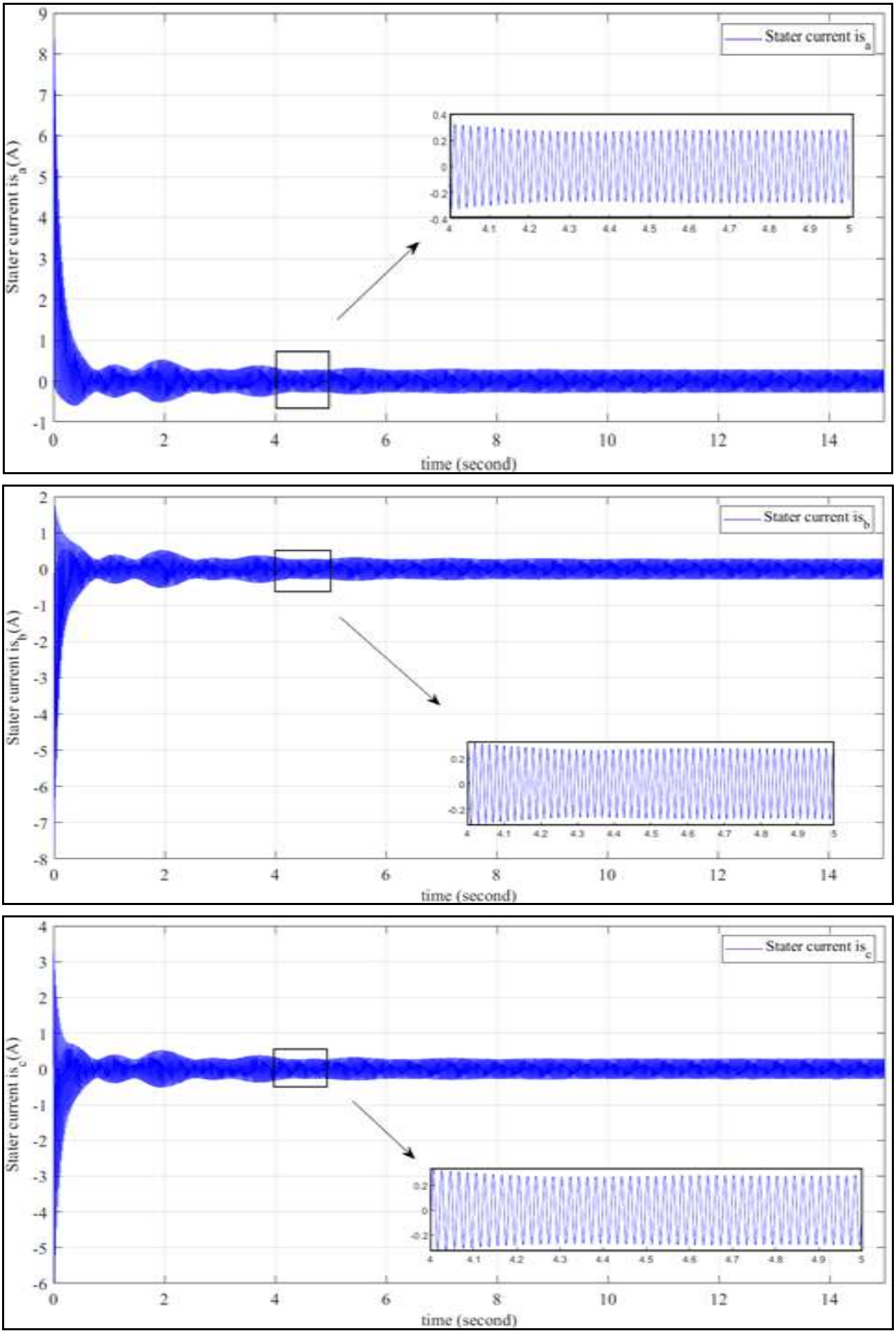
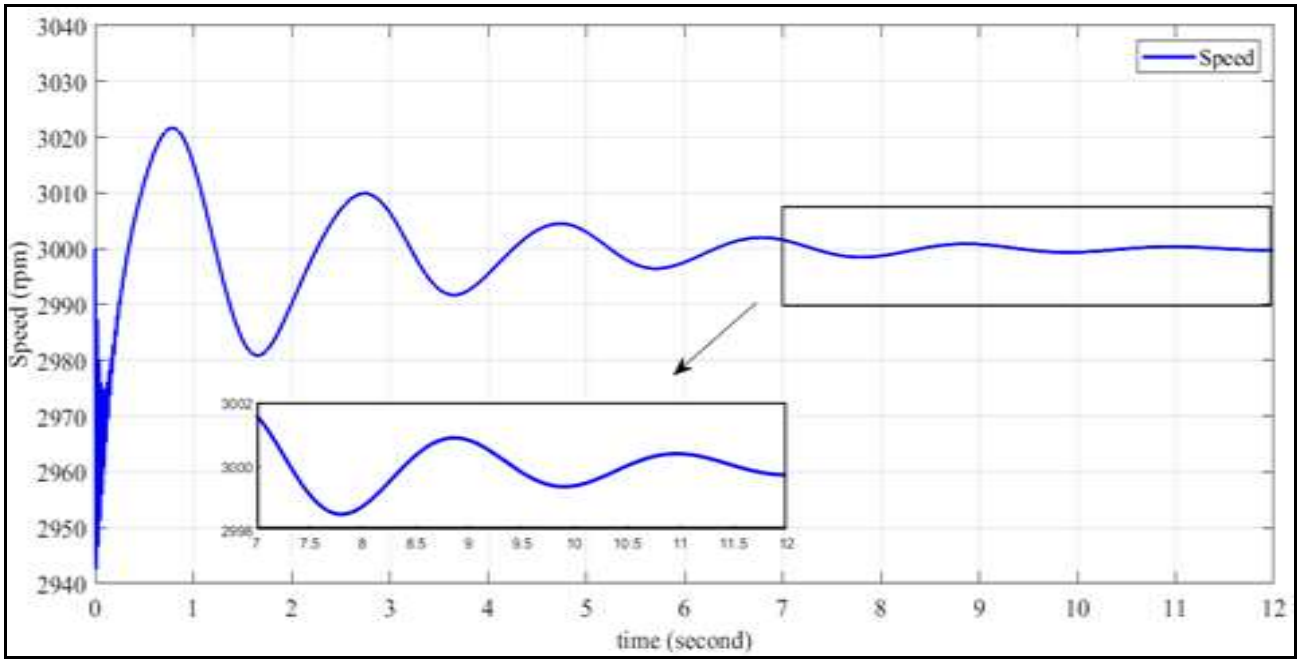
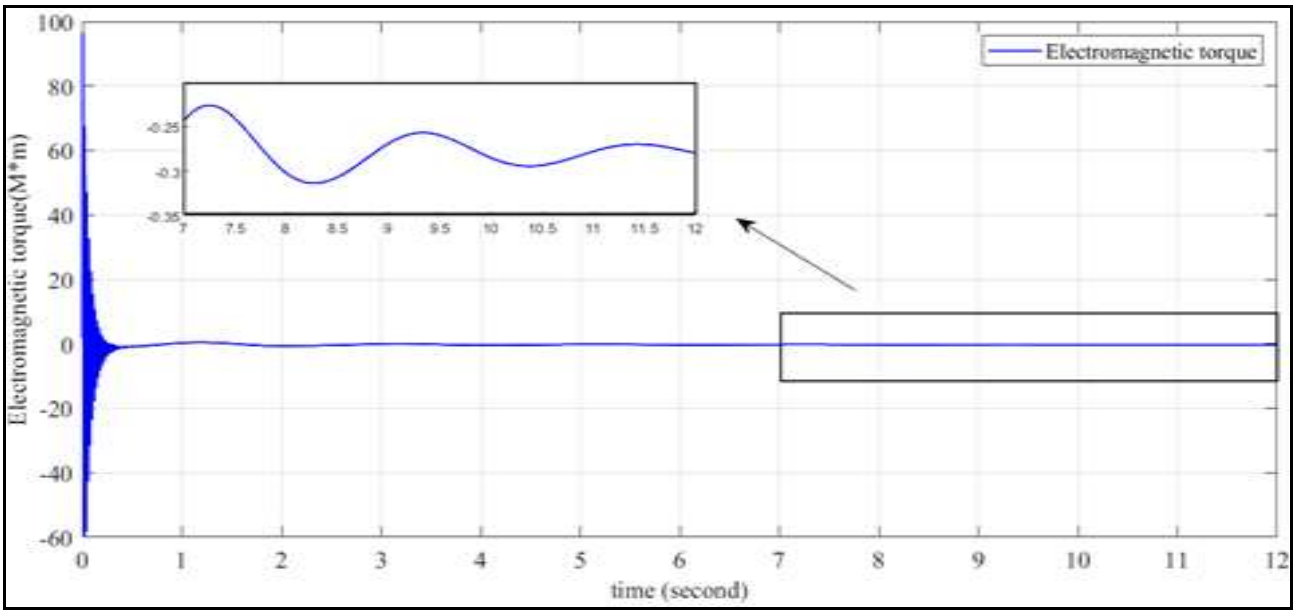
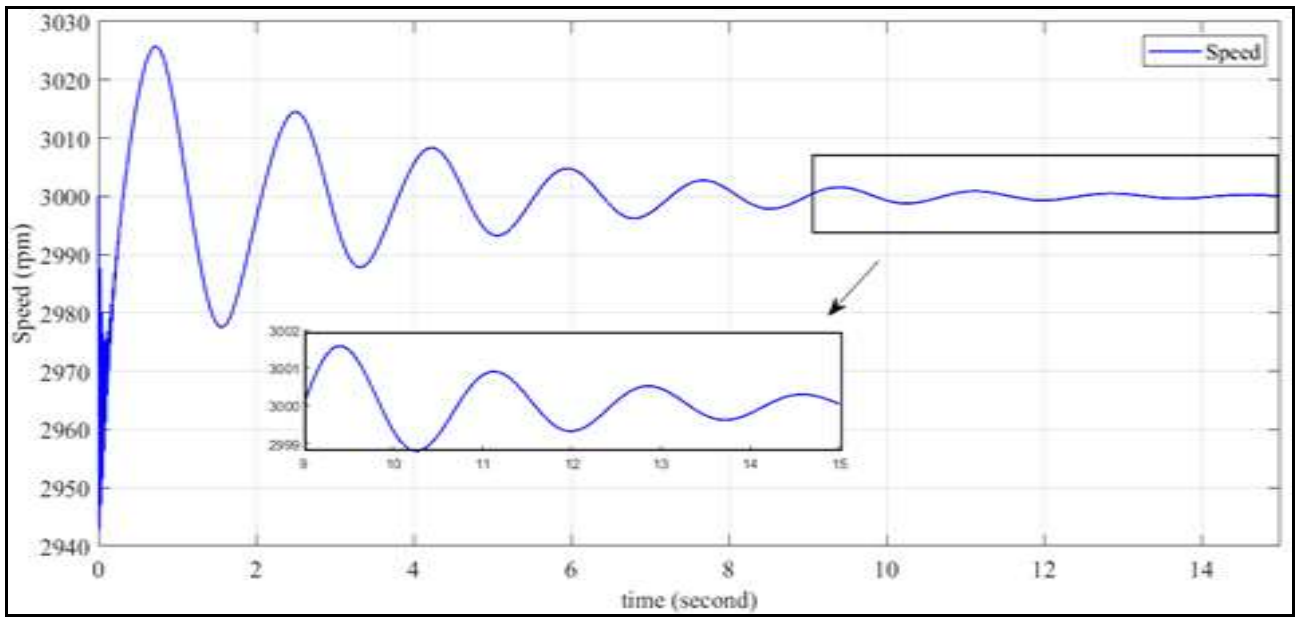


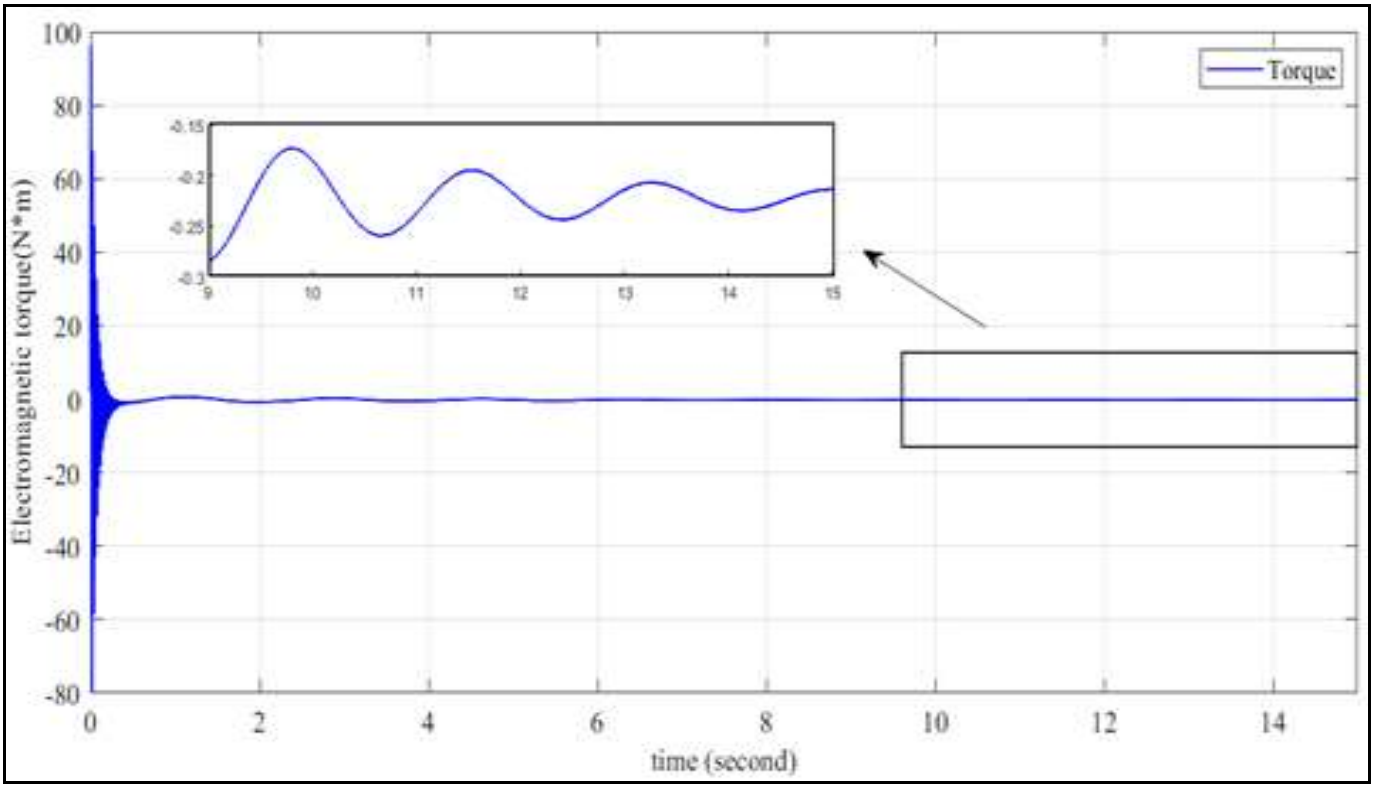
Fig 11: Stater Current for Leading Power Factor at Balance Supply Case





(a) Unity power factor





(b) Leading power factor

Fig 12: Speed and Torque Response for load Balance Supply Case

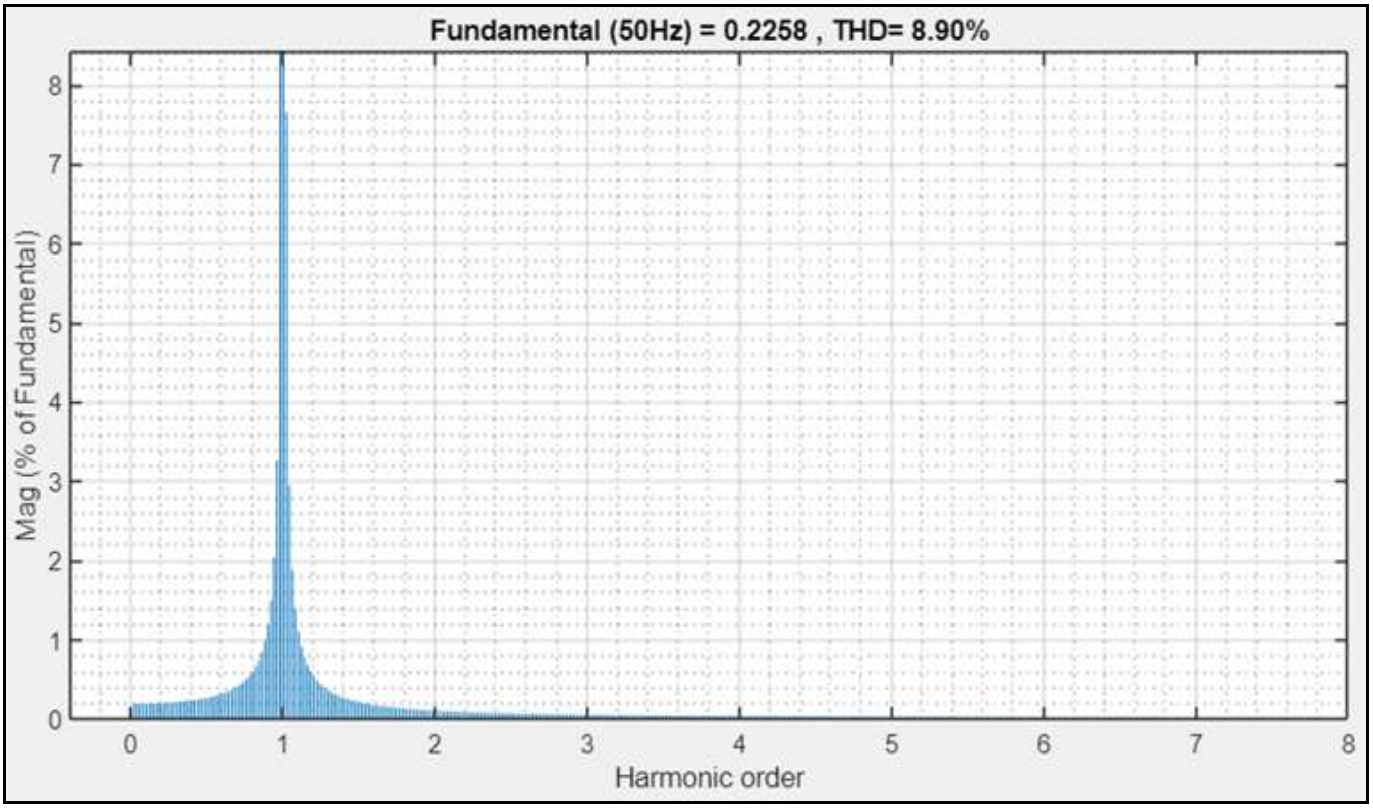


Fig 13: Harmonic and THD for 87.8w Load Unity Power Factor at Balance Supply Cas

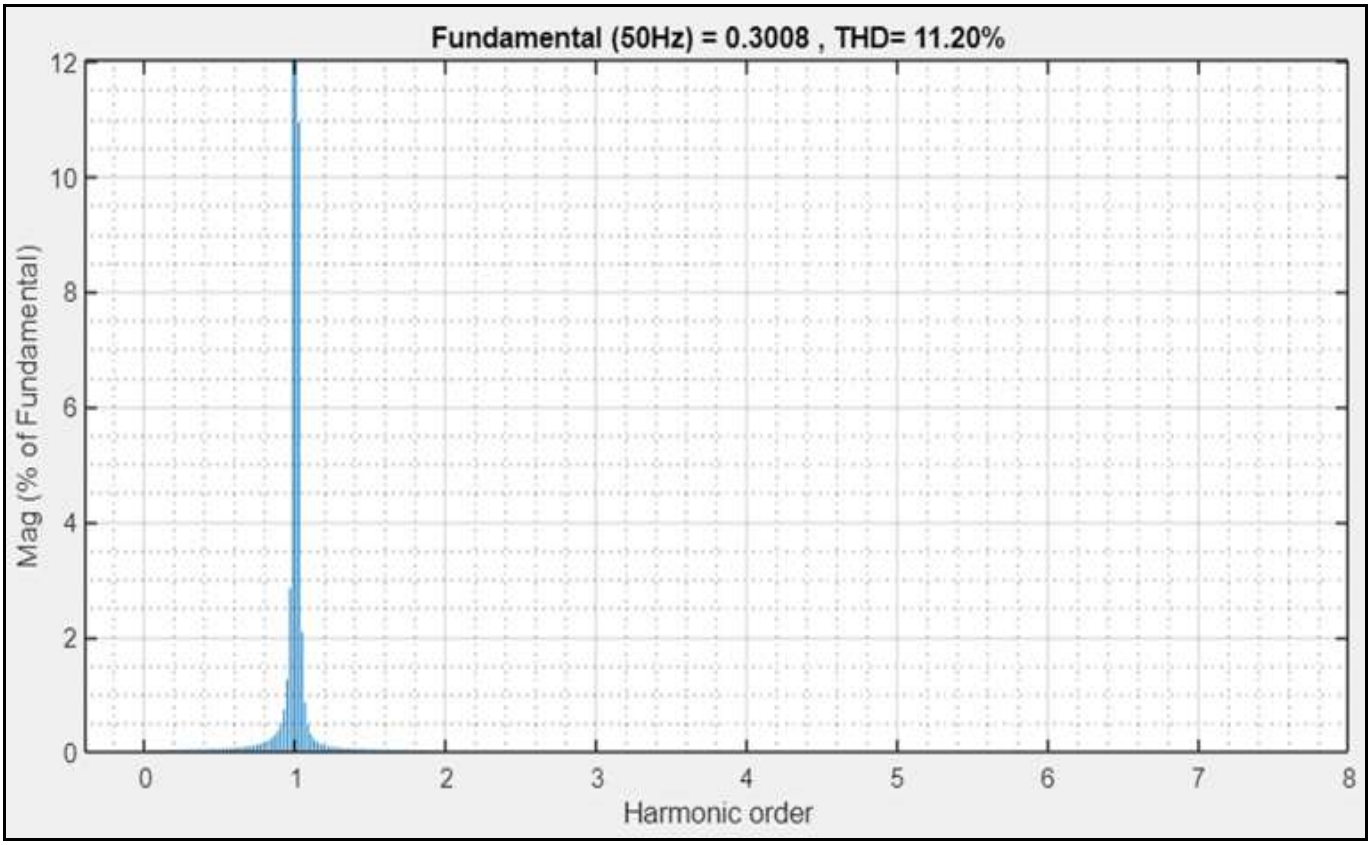


Fig 14: Harmonic and THD for 70w Load Leading Power Factor at Balance Supply Case

5. Equilibrium Sinusoidal Supply Simulation Results

This section examines the performance of a three-phase synchronous motor by applying imbalance fluctuations in the voltage's phase and magnitude in two different scenarios:

5.1 Under Voltage in Magnitude and Phases

Under unbalanced voltage, these readings were recorded with a load in case unity, leading power factor. Following are the voltages that were applied:

$V_a = 202\angle 0 \qquad V_b = 217\angle -116 \qquad V_c = 223\angle 119$

Table 3: Performance of Synchronous Motor at Unbalance Conditions (Under)

	Unity power Factor	Leading power Factor
$I_{sa}(A)$	$0.297\angle -144.8$	$0.313\angle -27.6$
$I_{sb}(A)$	$0.399\angle 84.68$	$0.2978\angle 87$
$I_{sc}(A)$	$0.1973\angle -34.31$	$0.4131\angle -131$
$I_{exc}(A)$	0.3176	0.425
$P_{in}(w)$	184.2	206.7
$Q_{in}(var)$	-27.3	-120
$P_{out}(w)$	87.8	70
$Eff.$	0.476	0.3338
$T(N*m)$	0.239	0.2323
$p.f$	0.9	0.82
$Speed$	3000	3000

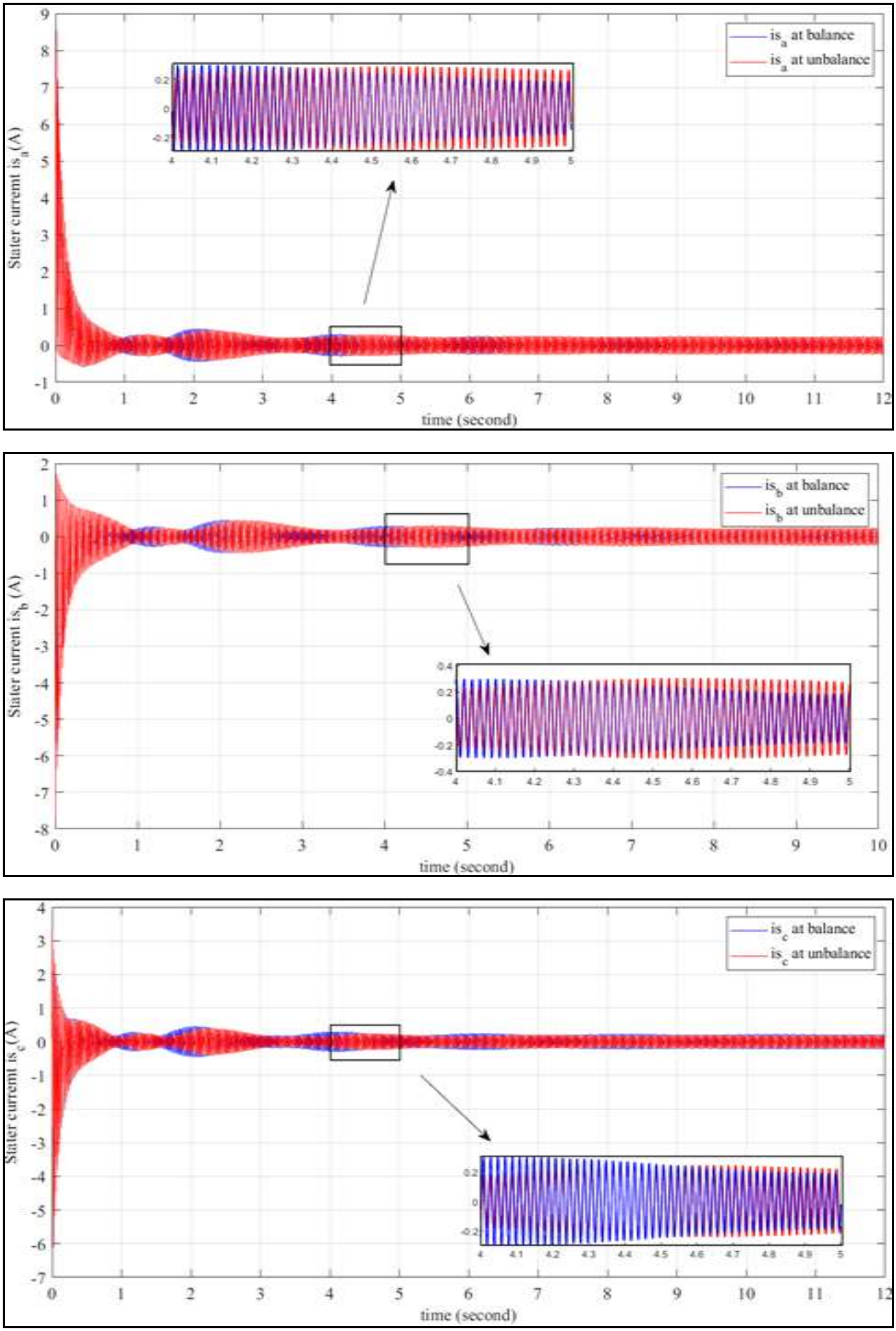


Fig 15: Stater Current for Load Unity Power Factor at Unbalance Supply

Case (Under)

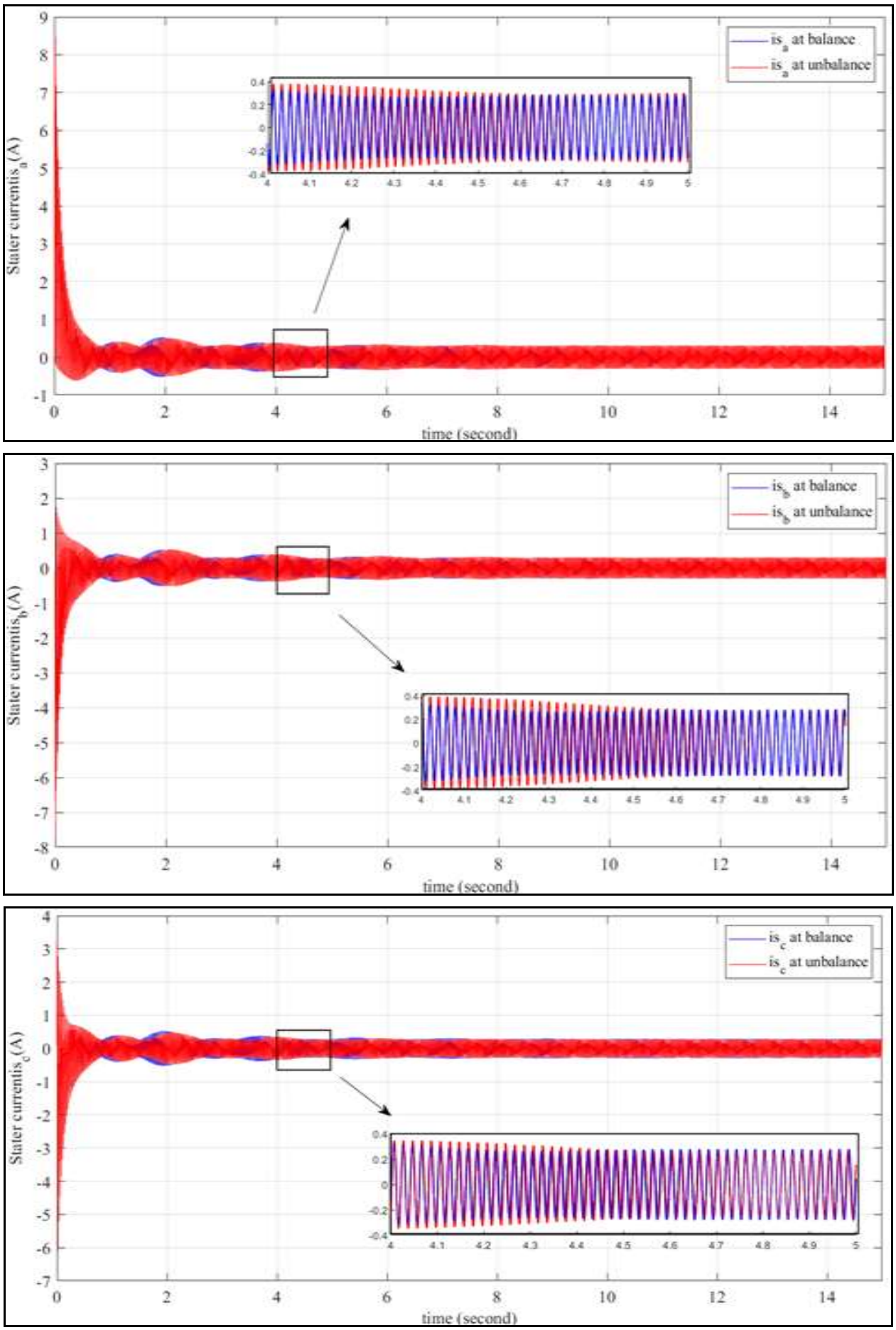
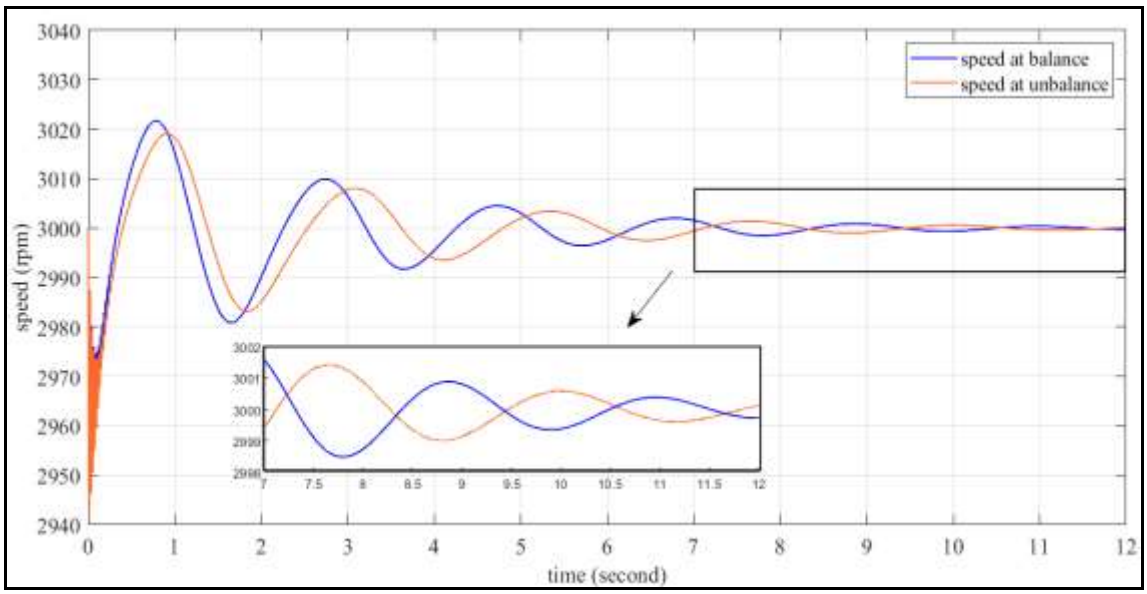
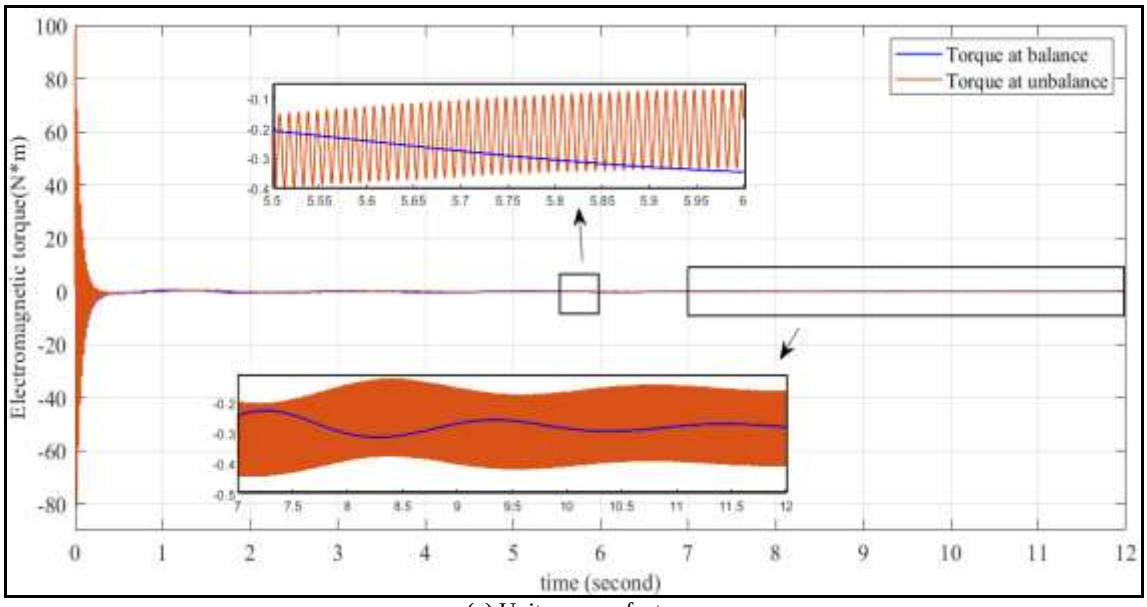


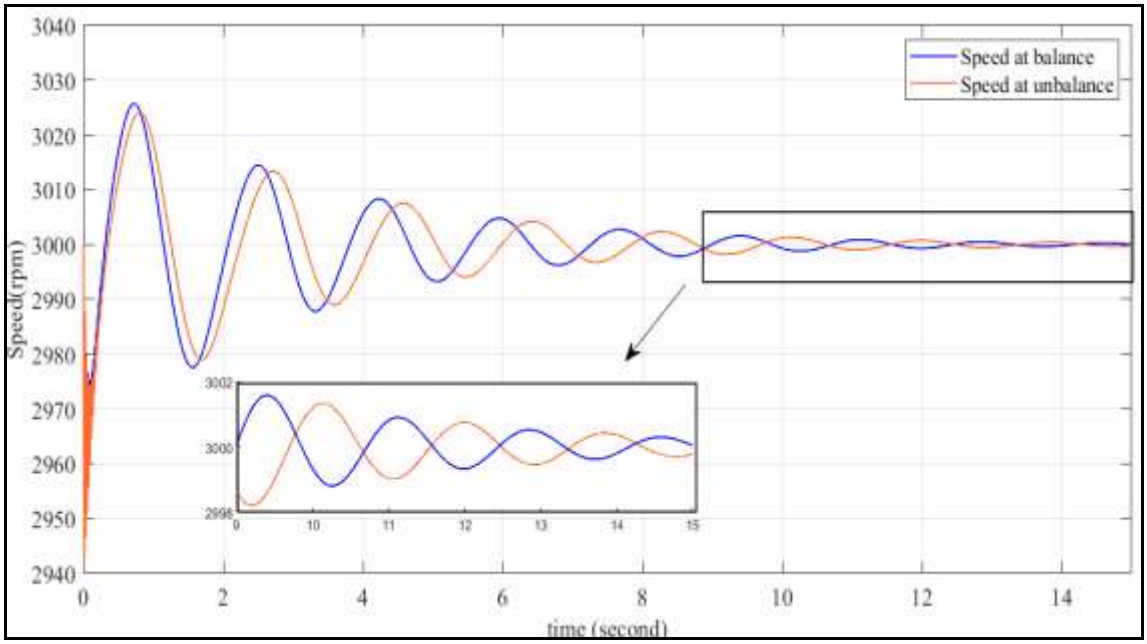
Fig 16: Stater Current for Leading Power Factor at Unbalance Supply

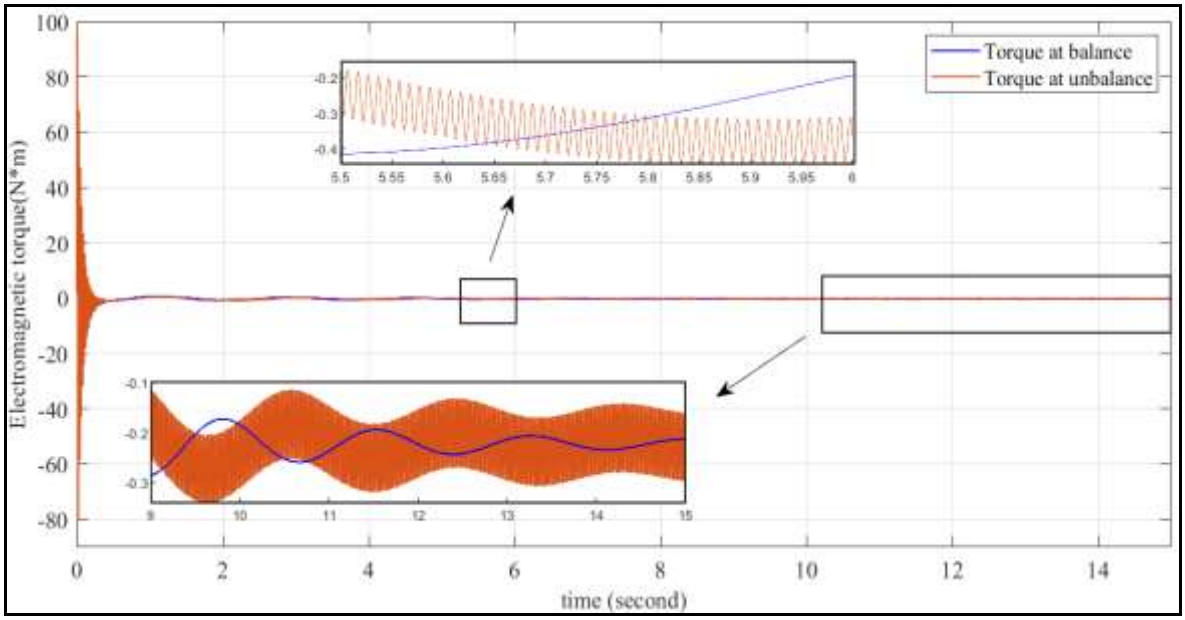
Case (Under)





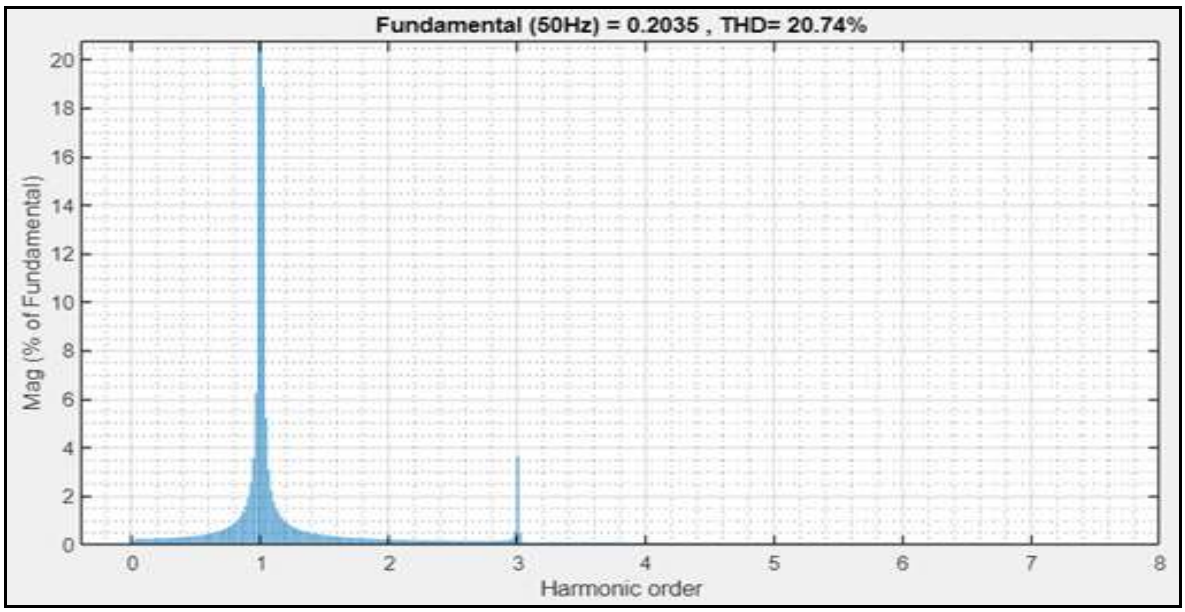
(a) Unity power factor

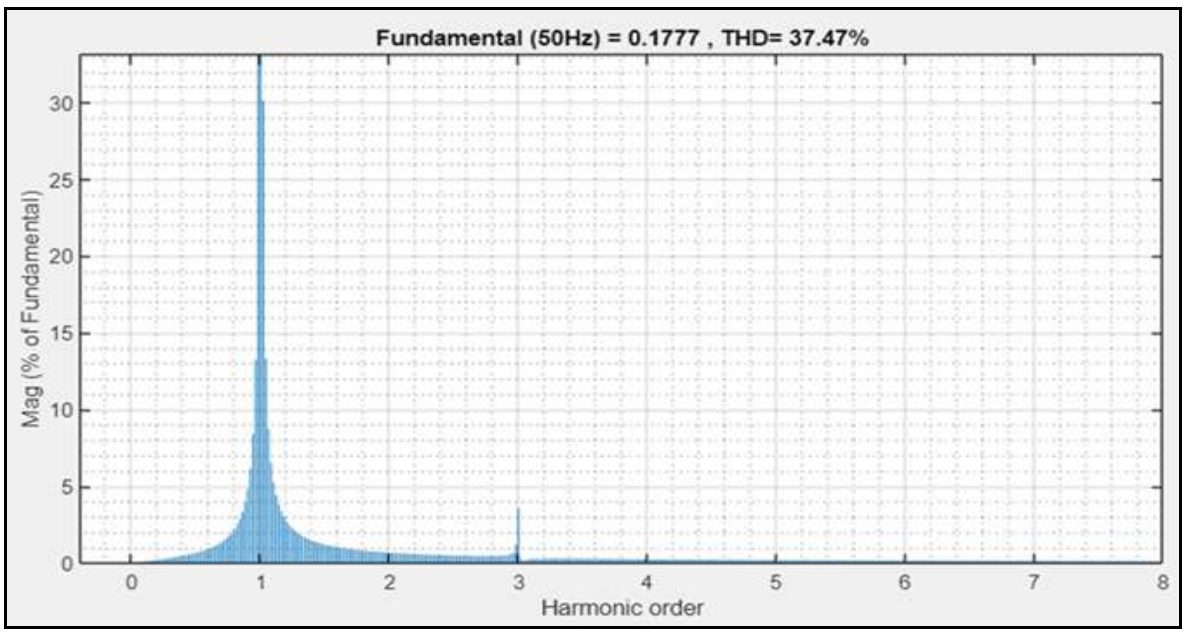




(b) Leading power factor

Fig 17: Speed and Torque Response for load Unbalance Supply Case (Under)





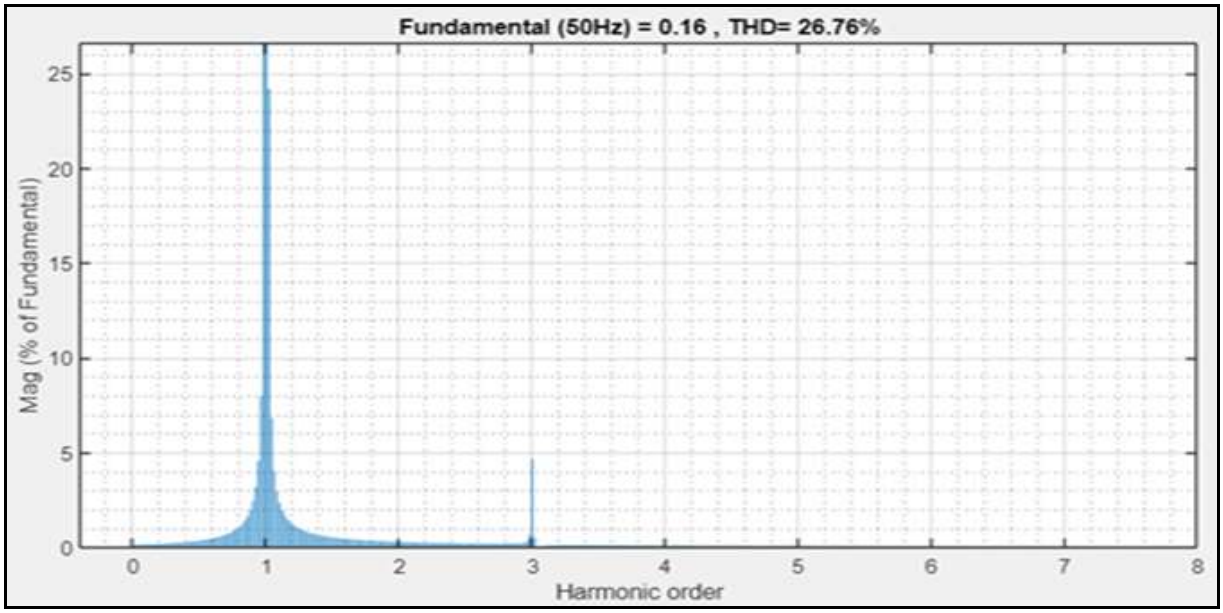
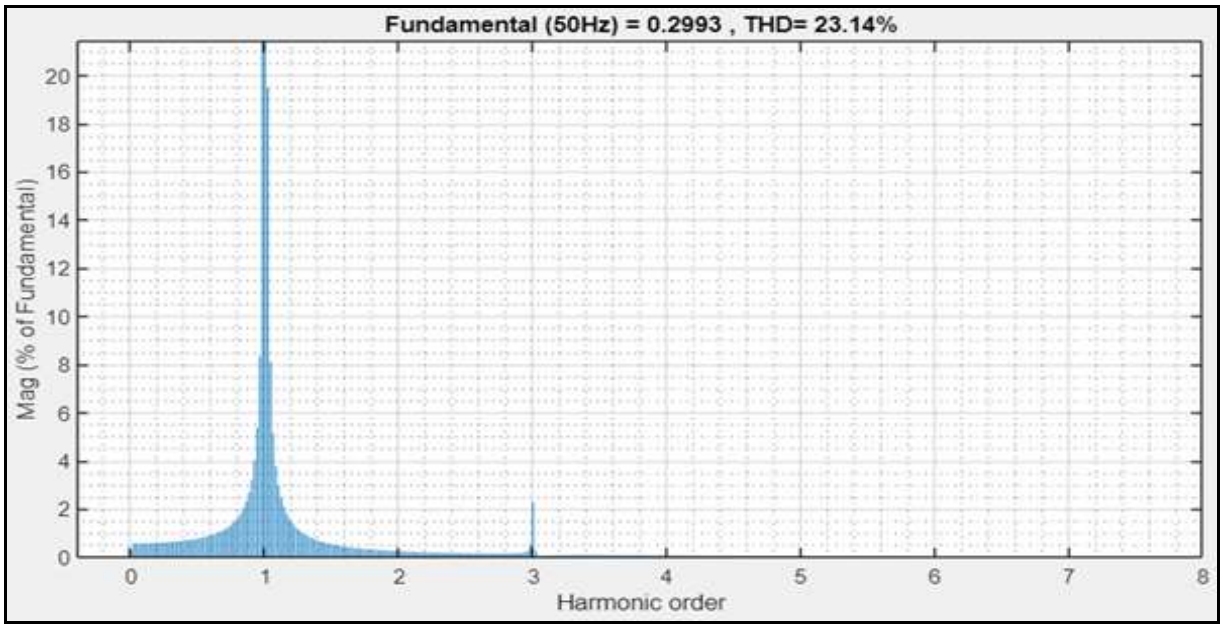
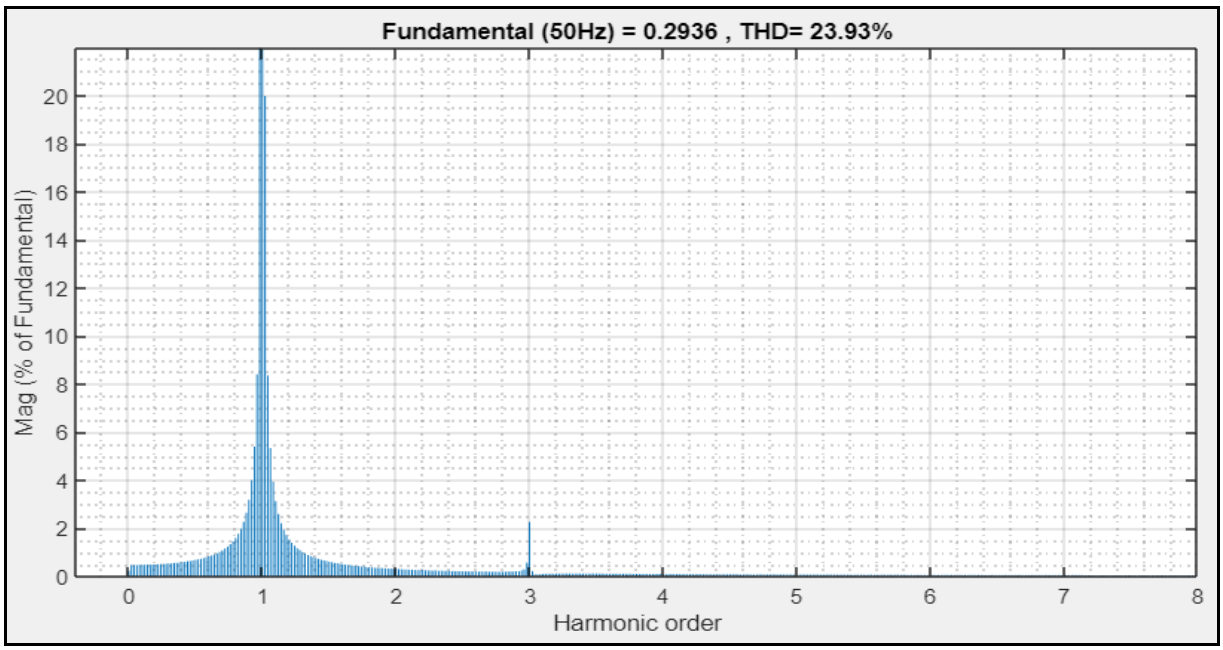


Fig 18: Total Harmonic Distortion of Stater Current for Unity power Factor at Unbalance Supply (Under)





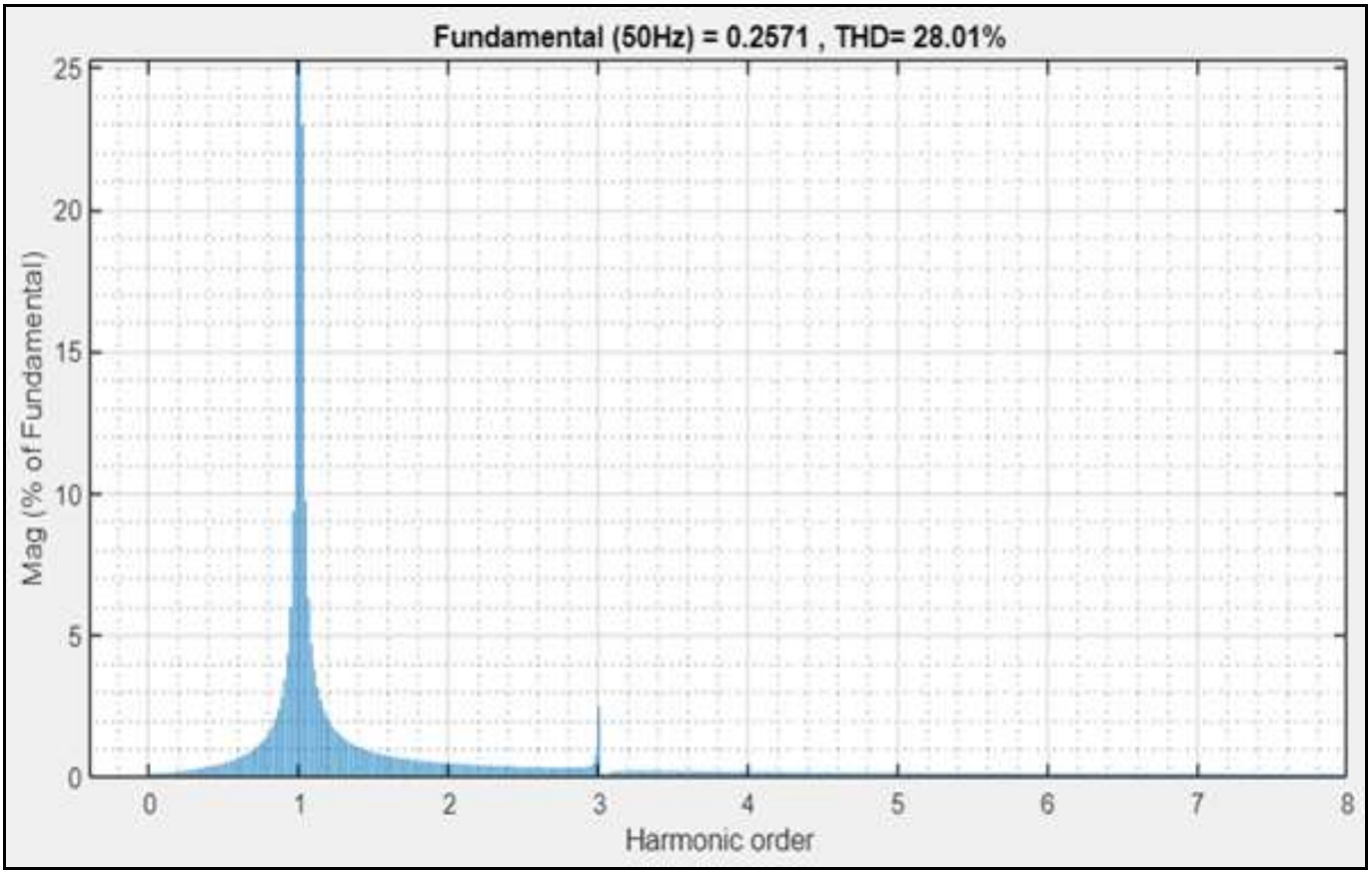


Fig 19: Total Harmonic Distortion of Stater Current for Leading power Factor at Unbalance Supply (Under)

5.2 Over Voltage in Magnitude and Phases

Under unbalanced voltage, these readings were recorded with a load in case unity, leading power factor. Following are the voltages that were applied:

$V_a = 245\angle 0 \qquad V_b = 239\angle -121 \qquad V_c = 237\angle 122$

Table 4: Performance of Synchronous Motor at Unbalance Conditions (Over)

	Unity power Factor	**Leading power Factor**
$I_{sa}(A)$	$0.1991\angle -151.8$	$0.2986\angle -122.6$
$I_{sb}(A)$	$0.2435\angle 97.48$	$0.2789\angle 121.6$
$I_{sc}(A)$	$0.2888\angle -28.06$	$0.312\angle -2.276$
$I_{exc}(A)$	0.31.75	0.425
$P_{in}(w)$	185.3	211
$Q_{in}(var)$	12.12	-106
$P_{out}(w)$	87.8	70
$T(N*m)$	0.3071	0.2414
$Eff.$	0.473	0.3317
pf	0.98	0.86
$Speed$	3000	3000

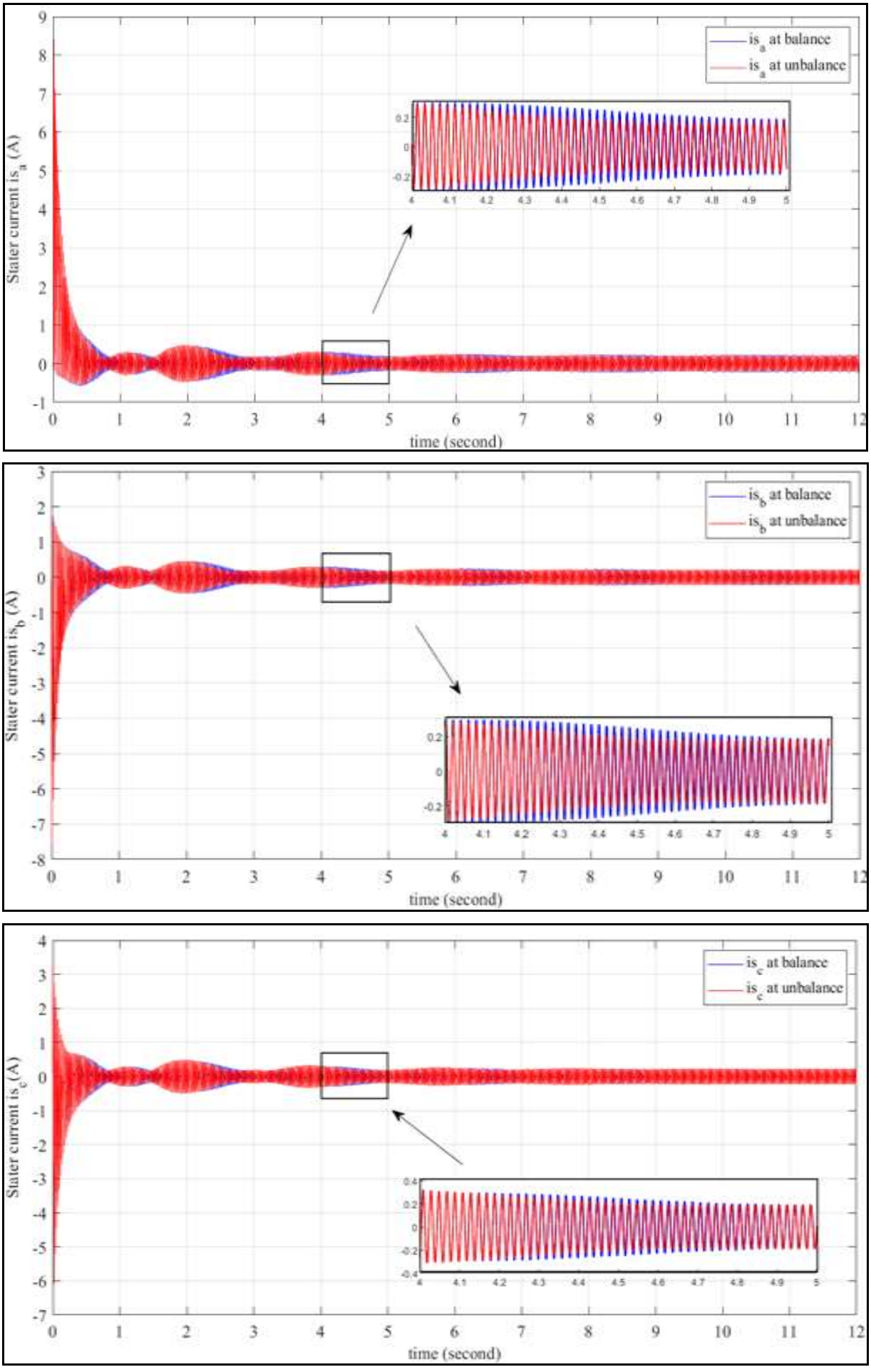


Fig 20: Stater Current for Unity Power Factor at Unbalance Supply Case (Over)

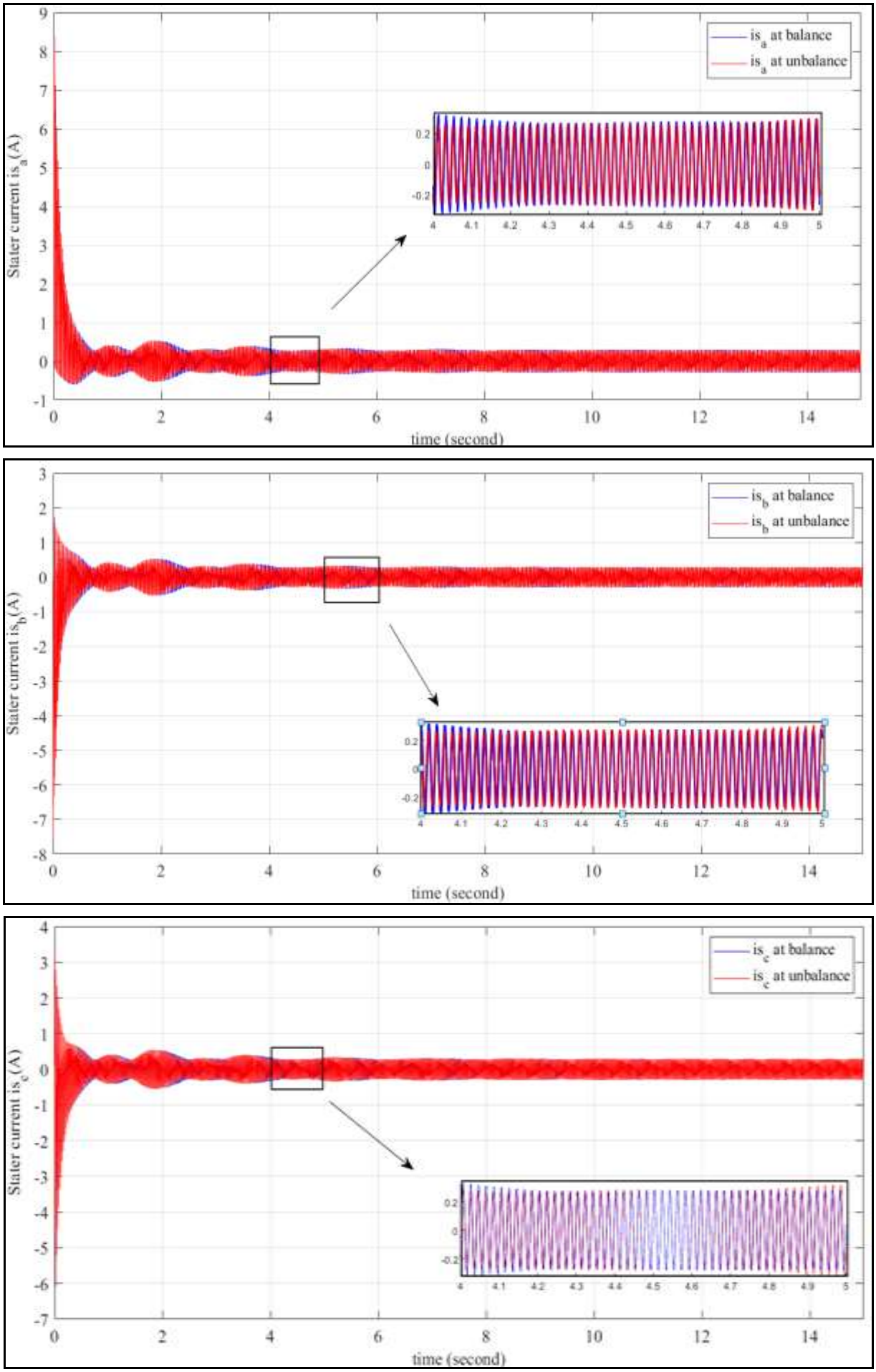
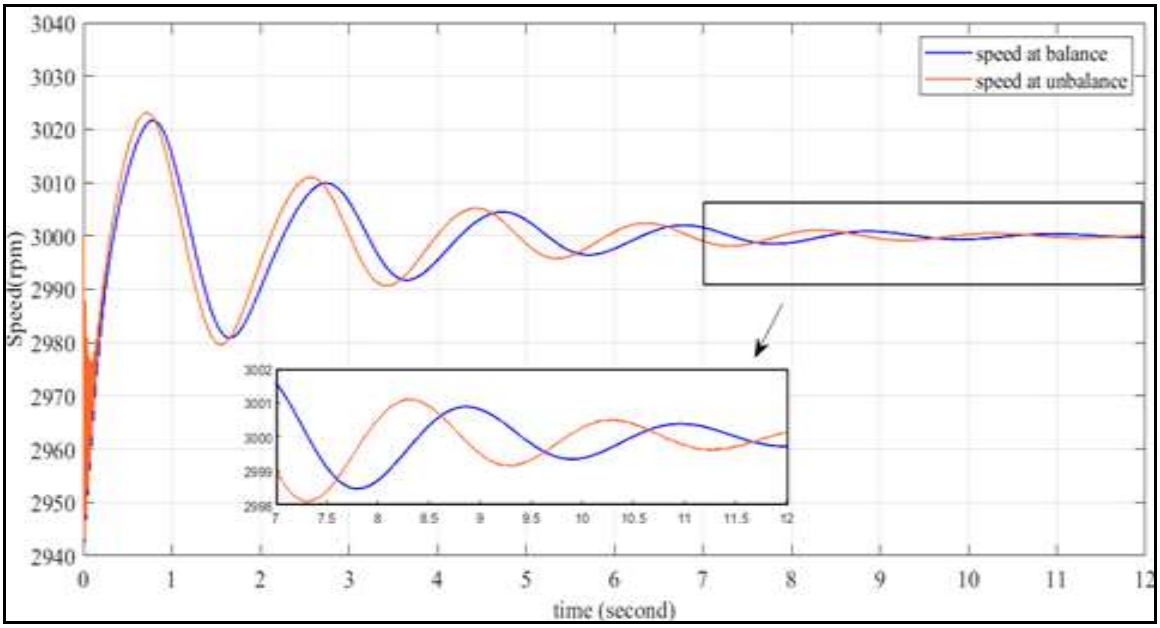
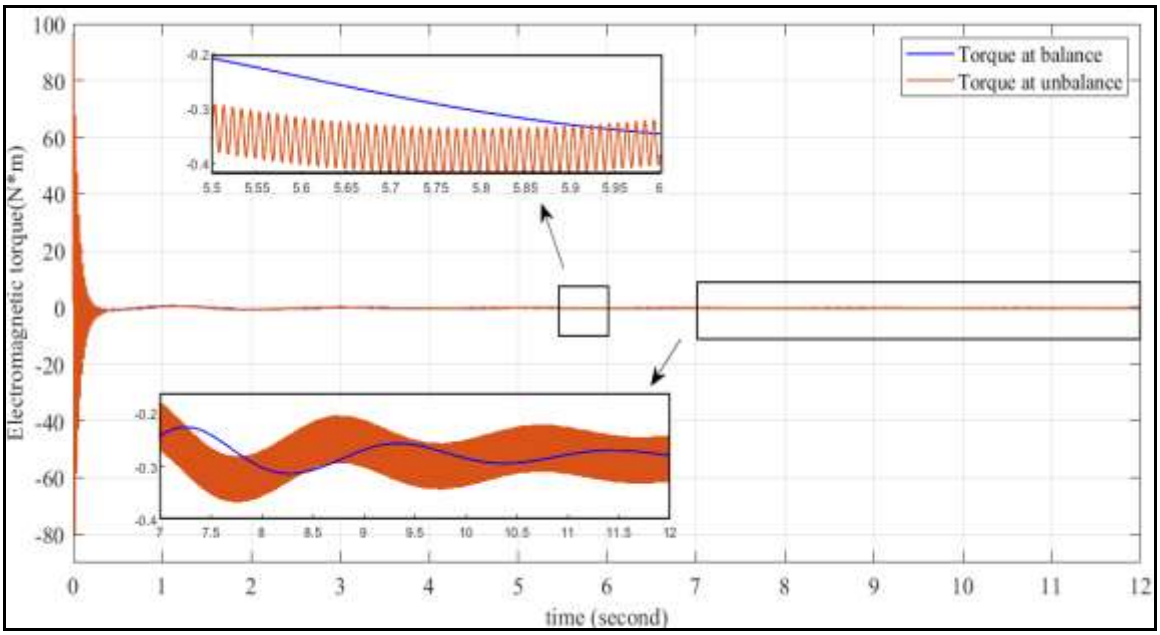
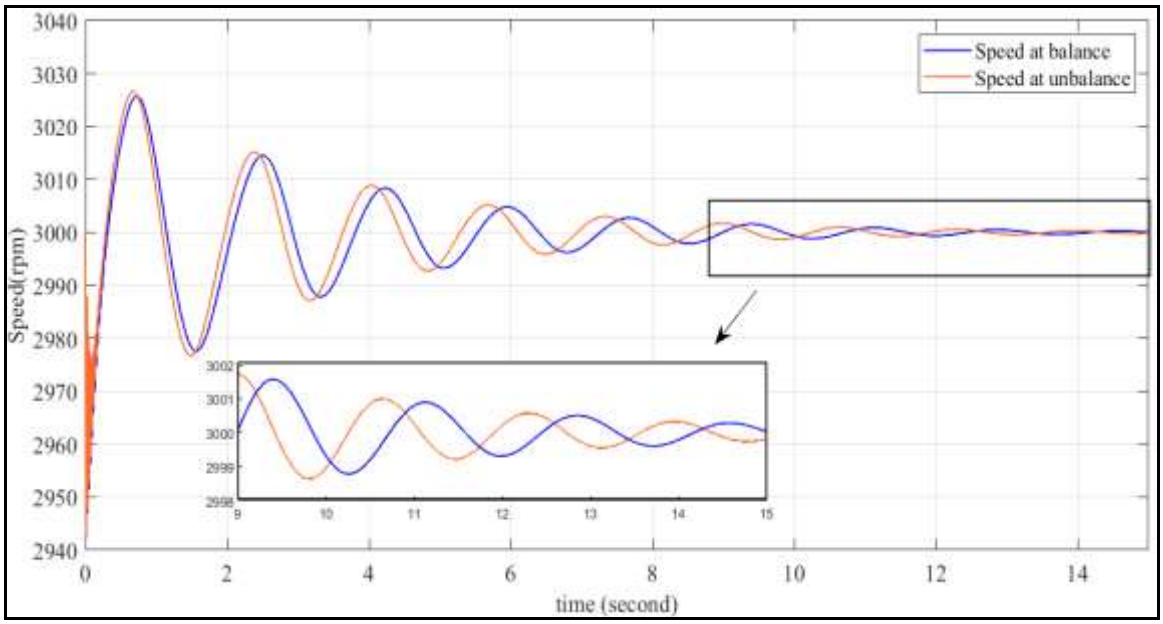


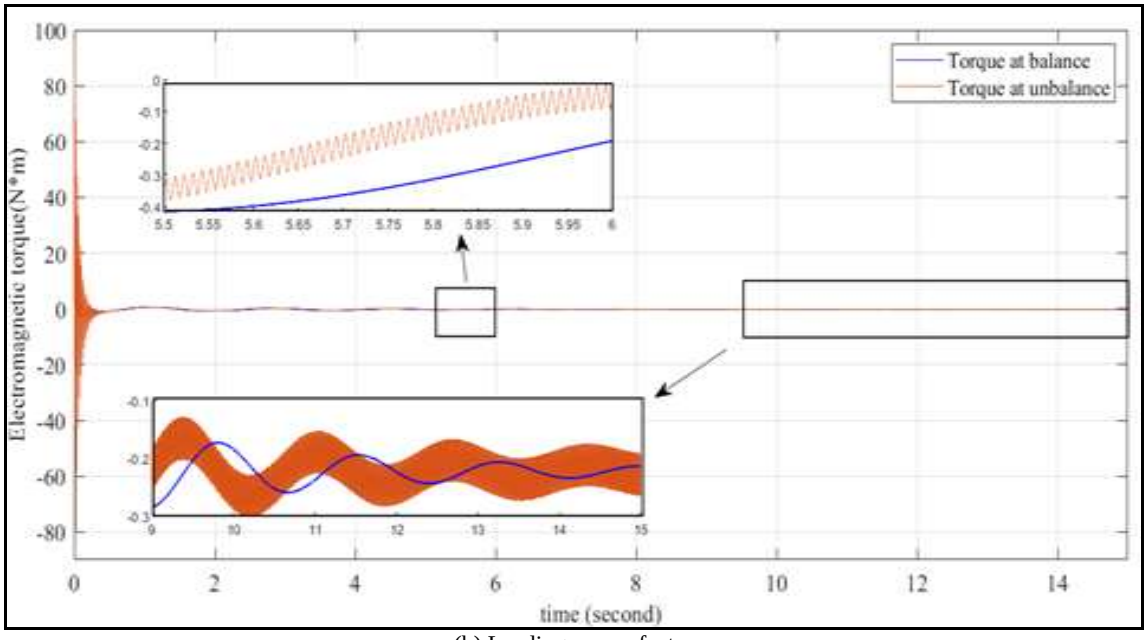
Fig 21: Stater Current for Leading Power Factor at Unbalance Supply Case (Over)





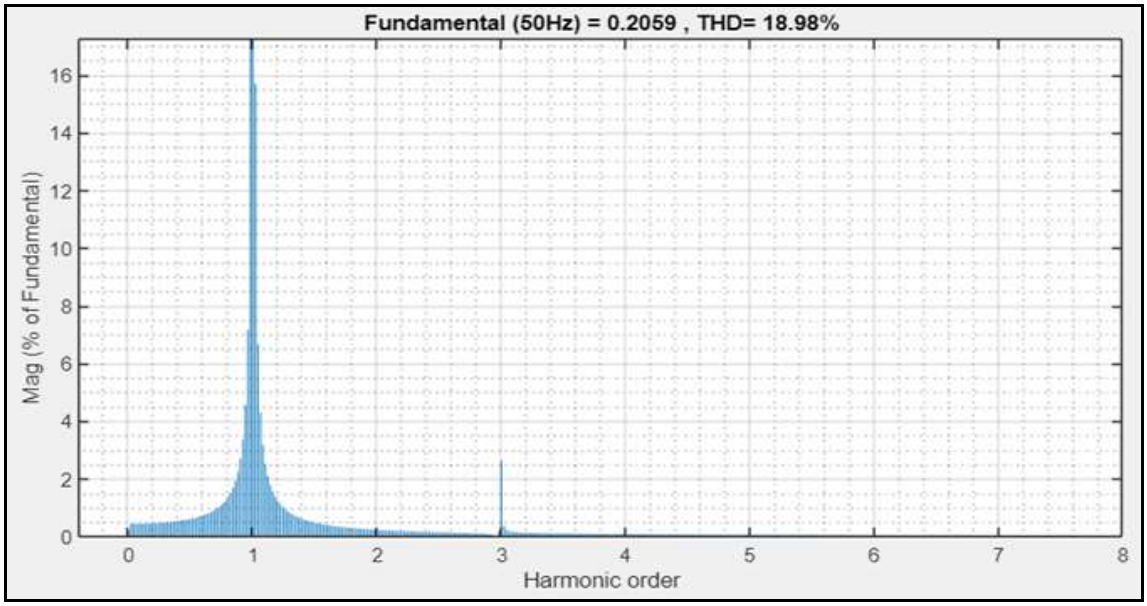
(a) Unity power factor

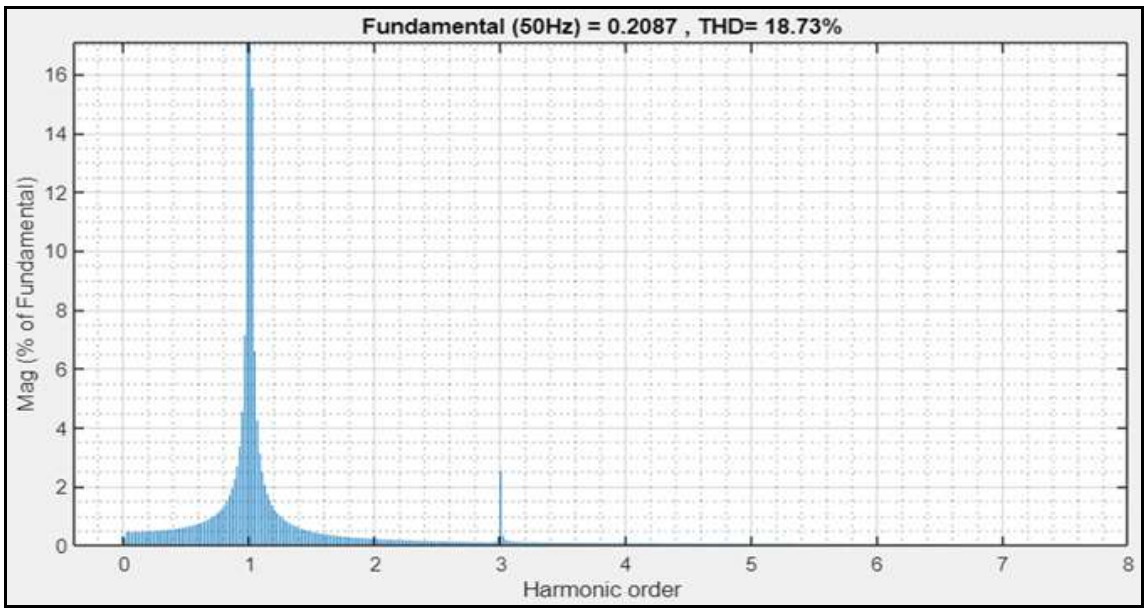




(b) Leading power factor

Fig 22: Speed and Torque Response for no load Unbalance Supply Case (Over)





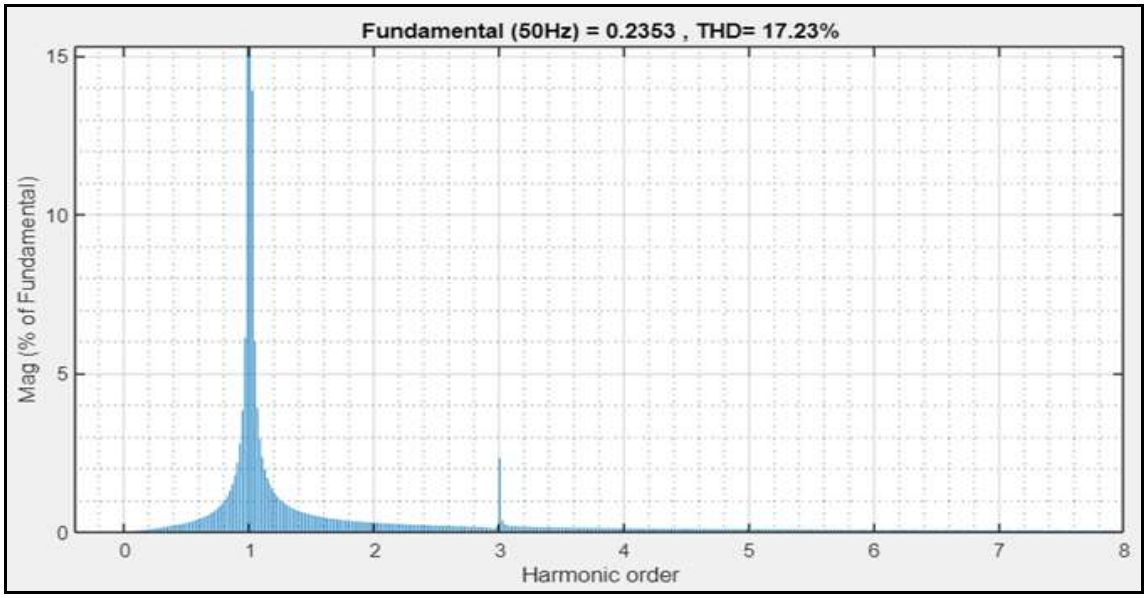
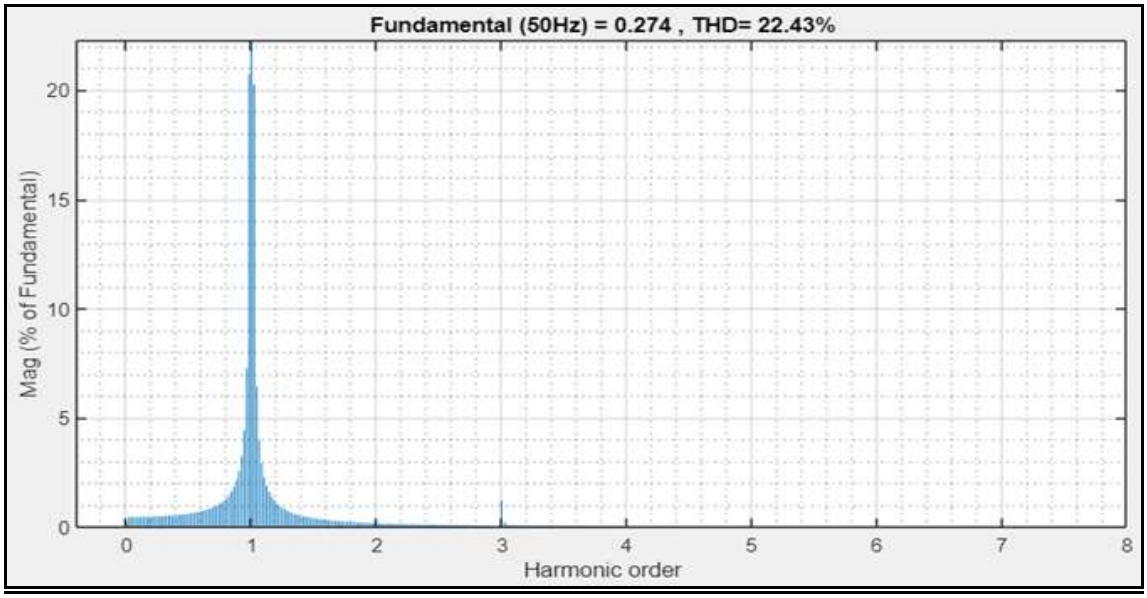
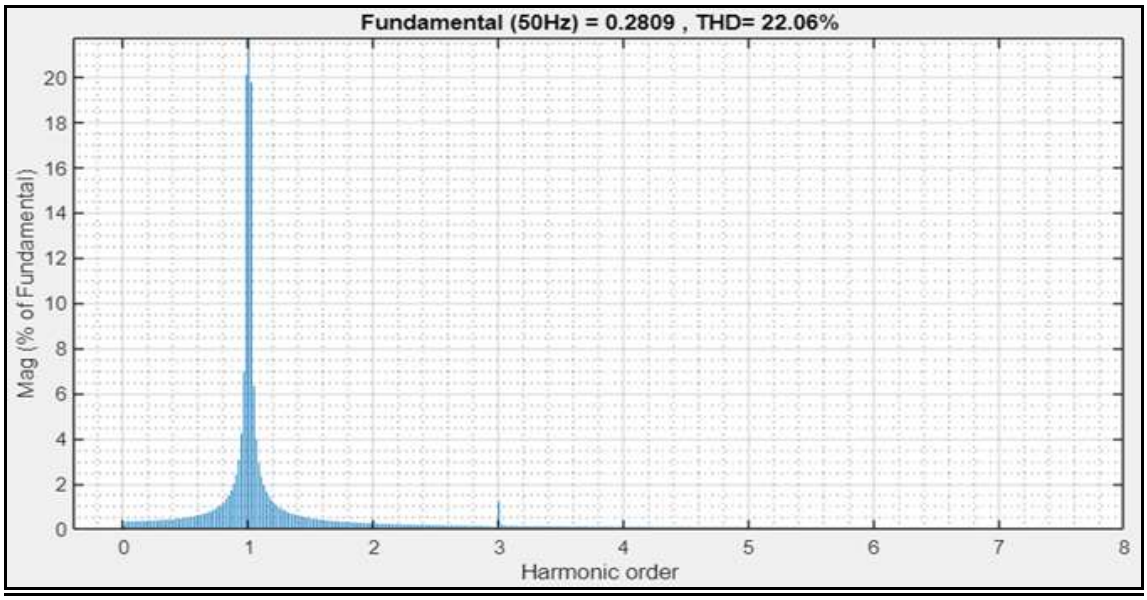


Fig 23: Total Harmonic Distortion of Stater Current for Unity power Factor at Unbalance Supply (Over)





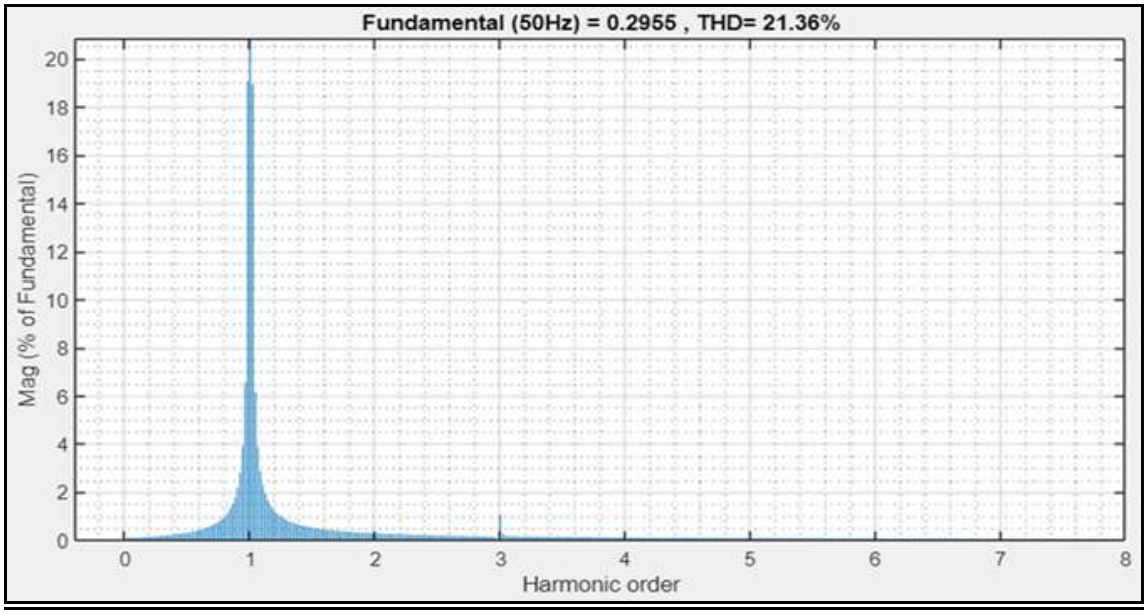


Fig 25: Total Harmonic Distortion of Stater Current for Leading power Factor at Unbalance Supply (Over)

6. Discuss of the Results

simulation results show that unbalanced voltage causes unbalanced phase current, with current increasing significantly some phases while, decreasing in other, hence it lead increasing power losses and decreasing efficiency. These unbalance currents in the motor- windings require more reactive power to be generated in order to make up for the voltage difference resulting from the imbalanced voltage. This increase in reactive power leads to decrease in the power factor.

The findings indicated that the torque production of the synchronous motor is negatively impacted by unbalanced voltage which produces oscillating torque, which compromises motor operation stability. A larger torque production is observed when the voltage is above the rated voltage but it is unstable, with the possibility of magnetic saturation and mechanical damage. while a lower torque is produced when the voltage is below the rated voltage because weak magnetic field. The synchronous speed was not affected by the unbalance voltage as a value, but we notice the appearance of a slight fluctuation around the nominal value because the voltage unbalance ratio was less than 10% an rise in the voltage imbalance ratio more than 10% may cause a clear fluctuation to take place.

Regarding THD, its values have increased above what they were when the voltage was balanced. The rise in THD has been found to be more affected by a decrease in voltage under the rated voltage than by an increase in voltage above the rated voltage. This is because the motor's internal magnetic flux is affected by low voltage, which distorts the electromagnetic wave. More undesirable harmonics are produced by this distortion.

7. Conclusion

The results signs that the current pulled by the motor in unbalanced voltage higher than the current drawn by the motor at balance voltage. Each of the three phases will draw unequal currents. Unbalanced current results in higher losses because of the coil's resistance, which causes the motor to overheat. Unwanted harmonic current is produced by unbalanced voltages. These harmonics decrease efficiency and cause the motor to lose more losses. Additionally, affect the rotor and raise the heat produced within it. It also generates high currents in the zero phase in practical system using neutral points, this may lead to additional problems in distribution or protection networks. A synchronous motor's speed is not directly impacted by a voltage imbalance because it depends on the electrical frequency of the network and the number of motor poles, not voltage. As long as the frequency stays constant, the synchronous speed won't change. But the motor's operation may be affected by a voltage imbalance even if the synchronous speed is constant. For instance, increased vibration. When an imbalanced voltage results in unbalanced currents flowing through the motor's windings, creating a negative component in the magnetic field. These components produce counterforce, which causes disruptions and mechanical vibrations.

When the motor operates in a leading power factor, it takes longer for the motor to reach synchronous speed than when it operates in a unity power factor. The motor consumes only active power, and the current is precisely proportionate to the voltage. The performance in this instance is rather constant and balanced, and the time required to reach synchronous speed is typical and unaffected by additional factors. But the leading power factor in contrast to the unity case, the motor produces an effective reactive power that amplifies the effect of magnetizing current (Over-excitation). This could result in more oscillations that postpone the motors' settling at synchronous speed and lengthen the access time.

Unbalanced voltage produces zero, negative, and positive sequence components. Negative sequential component causes torque oscillation and results in low torque generation.

Unbalanced voltages affect the synchronous motor based on the power factor. These effects manifest as changes in power factor, harmonic, efficiency, and electrical current.

References

1. Zaretskiy A. Mathematical models and stability analysis of three-phase synchronous machines. Diss. University of Jyväskylä; c2013.
2. Jäger C, Grinbaum I, Smajic J. Dynamic short-circuit analysis of synchronous machines. IEEE Trans Magn. 2017;53(6):1-4.
3. Cristea C, Stroe I. The study of the synchronous motor. Bull Transilv Univ Brasov Ser I Eng Sci. 2017;31-38.
4. Faria VD, Bernardes Jr JV, Bortoni EC. Parameter estimation of synchronous machines considering field voltage variation during the sudden short-circuit test. Int J Electr Power Energy Syst. 2020;114:105421.
5. Ma Y, Zhou L, Wang J. Standstill time-domain response parameter estimation of the large synchronous condenser in arbitrary rotor position. IEEE Access. 2020;8:166047-166059.
6. Ferreira FJTE, De Almeida A, Cistelecan M. Voltage unbalance impact on the performance of line-start permanent-magnet synchronous motors. In: Proceedings of the 6th International Conference EEMODS, Nantes, France; c2009.
7. Ferreira FJTE, De Almeida A, Cistelecan M. Voltage unbalance impact on the performance of line-start permanent-magnet synchronous motors. In: Proceedings of the 6th International Conference EEMODS, Nantes, France; c2009.
8. Qadir B. Investigate the performance characteristics of three-phase synchronous machine. Meas Sens. 2023;29:100811.
9. Carpiuc SC, Lazar C. Modeling of synchronous electric machines for real-time simulation and automotive applications. J Franklin Inst. 2017;354(14):6258-6281.
10. Onah CO, Reuben J. Dynamic modelling and simulation of salient pole synchronous motor using embedded Matlab. Am J Eng Res. 2016;5:318-325.
11. Moeini A, *et al*. Synchronous machine stability model, an update to IEEE Std 1110-2002 data translation technique. In: 2018 IEEE Power & Energy Society General Meeting (PESGM); c2018.
12. O'Rourke CJ, *et al*. A geometric interpretation of reference frames and transformations: dq0, Clarke, and Park. IEEE Trans Energy Convers. 2019;34(4):2070-2083.