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Comprehensive Power System Studies Of A 13.8 Kv Network Including Load Flow, Short Circuit, Motor Acceleration, Power Factor Improvement, Transient Stabilities And Harmonic Analysis Using Etap

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Abstract- — This project presents comprehensive power system studies of a 13.8 kV substation network to improve power quality and operational reliability. Load flow analysis is carried out to evaluate voltage profiles, power losses and reactive power flow while maintaining a minimum lagging power factor of 0.95 at the Point of Common Coupling. Short circuit analysis is performed to determine fault current levels and verify equipment and protection adequacy. Motor acceleration studies assess starting currents, voltage dips and dynamic performance of large motors. Power factor improvement is achieved through optimal selection and placement of capacitor banks. The impact of capacitor switching, including transients and self excitation effects is evaluated. Harmonic analysis is conducted to ensure acceptable distortion levels. Transient stability of the system during disturbances is analyzed using ETAP. The study demonstrates improved voltage stability, reduced losses and enhanced system reliability.

Keywords: ETAP, Power Factor Improvement, Motor Acceleration.

I. INTRODUCTION

Electrical power systems at the 13.8 kV voltage level are widely used in industrial and utility applications to supply large and critical loads. The increasing integration of high- capacity motors and nonlinear power electronic equipment has increased system complexity. Comprehensive power system studies are essential to ensure reliable and efficient operation. Load flow and short circuit analyses evaluate steady state performance and fault levels of the network. Motor acceleration, transient stability and power factor improvement studies assess system behaviour under dynamic conditions. Harmonic analysis is performed to evaluate power quality issues and overall system performance using integrated simulation tools such as ETAP.

II. LITERATURE SURVEY

Alabi and Singh et al (2022) reviewed applications of ETAP for load flow and short- circuit studies. The paper discussed modeling techniques and analysis capabilities. ETAP's graphical interface was highlighted as a key advantage. Integrated studies were found beneficial for system validation. The review confirmed ETAP's effectiveness in industrial power system studies.

Al-Daajeh and Tuffaha et al (2018) evaluated different power factor improvement techniques in distribution systems. The study showed reduced losses and improved voltage regulation after compensation. Capacitor banks proved economical for industrial applications.

AlRashidi and Massoud et al (2019) investigated short-circuit current levels in distribution systems with distributed generation. Their analysis showed that DG significantly alters fault currents and protection coordination. Regular fault level reassessment was recommended.

El-Sayed and Mortada et al (2020) analyzed motor starting transients in industrial distribution networks. Voltage dip magnitude and duration were evaluated. Different starting methods were compared. Soft starters and VFDs reduced system disturbances significantly. The study demonstrated the importance of motor acceleration analysis.

Kumar et al (2020) carried out load flow studies on medium-voltage distribution networks using ETAP. The research focused on voltage profile analysis and real–reactive power flow assessment. Different loading conditions were simulated to evaluate system performance. The results showed good convergence and accuracy of ETAP solvers.

The study concluded that load flow analysis is essential for system planning and operation.

Ochoa and Harrison et al (2018) studied the effect of large induction motor starting on voltage stability. Direct-on-line starting was shown to cause significant voltage dips. The impact on sensitive loads was analyzed. Alternative starting methods were evaluated. Controlled starting techniques were recommended to improve system performance.

Patel and Bansal et al (2019) studied harmonic distortion in industrial networks caused by nonlinear loads. Simulation results indicated excessive THD levels beyond acceptable limits. Passive and hybrid filters were found effective for harmonic mitigation.

Singh and Kumar et al (2020) conducted transient stability analysis for 13.8 kV power systems under fault conditions. Critical clearing times were determined for different fault scenarios. The influence of large motors on system stability was evaluated. Results showed that stability margins decrease during severe disturbances. The study emphasized the need for dynamic stability assessment.

Wu and Wang et al (2018) compared different load flow algorithms for medium- voltage distribution networks. The convergence behavior under heavy loading conditions was analyzed. Unbalanced system conditions were also considered. Improved numerical methods enhanced solution reliability. The study supported accurate steady-state modeling of distribution systems.

Zhang et al (2020) investigated harmonic mitigation techniques using advanced filter configurations. Different filter topologies were compared for industrial applications. Simulation results showed substantial reduction in current and voltage harmonics. Hybrid filters provided better performance than conventional solutions. The study confirmed the importance of harmonic analysis in power system design.

III. DESCRIPTION OF EXISTING SYSTEM

The existing electrical system operates at the 13.8 kV level and supplies power to various industrial loads, including large motors and auxiliary equipment. The network consists of generators or utility supply, transformers, distribution feeders, switchgear and protective devices arranged in a conventional radial configuration. System operation is primarily focused on meeting load demand under steady- state conditions. Reactive power compensation is limited and often implemented using fixed capacitor banks without detailed optimization. Short-circuit levels and protection coordination are based on initial design data, with limited periodic reassessment. Harmonic distortion and dynamic performance during motor starting or disturbances are not comprehensively evaluated, indicating the need for integrated analytical studies.

IV. DESCRIPTION OF PROPOSED SYSTEM

The proposed system involves a comprehensive analysis of the 13.8 kV electrical power network using an integrated simulation approach. The entire network is modeled in ETAP to accurately represent generators, transformers, cables, motors, protection devices, and nonlinear loads. Load flow analysis is carried out to evaluate voltage profiles, power flow distribution and system losses under normal operating conditions. Short-circuit analysis is performed to determine fault current levels and to validate equipment ratings and protection coordination. Motor acceleration studies are included to assess voltage dips and starting performance of large motors. Power factor improvement is achieved through optimal placement and sizing of reactive power compensation devices. Transient stability analysis is conducted to examine system response under disturbance conditions. Harmonic analysis is performed to assess total harmonic distortion and to design appropriate mitigation measures. The proposed integrated approach enhances system reliability, efficiency, and power quality.

ETAP (Electrical Transient Analyzer Program)

The most comprehensive analysis platform for the design, simulation, operation, and automation of generation, distribution, and industrial power systems.

Benefits of ETAP

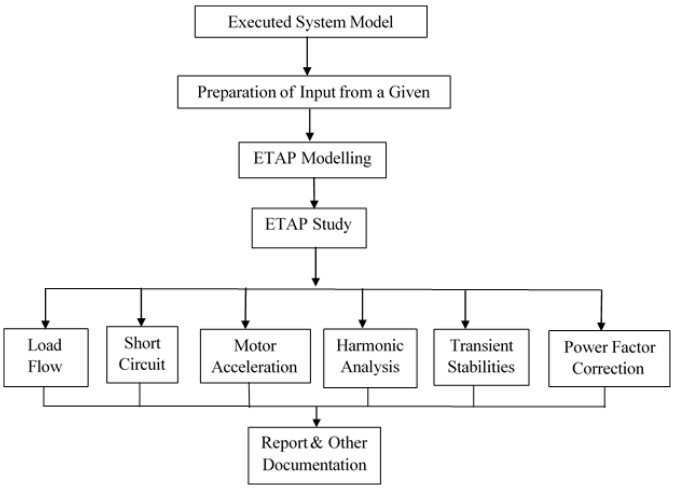
To create an electrical digital twin and analyze electrical power system dynamics, transients and protection which helps engineers design and manages energy and utility systems more effectively.

USAGE OF ETAP SOFTWARE

It is the most comprehensive analysis platform for the design, simulation, operation, and automation of generation, distribution, and industrial power systems.

ETAP is used to analyze power system performance and ensure safe, reliable, and efficient operation of electrical networks.

Executed Flow Of Work



Here the executed system models are given, we have to prepare the input from the given data, and then ETAP modeling and analysis are reported.

Study Done Using Etap Software

Load Flow Study.
Short Circuit Study.
Motor Acceleration.
Transient Stabilities.
Harmonic Analysis.
Power Factor Correction.

V. SYSTEM MODELING

The source is modelled with equivalent maximum & minimum short circuit currents at 26KV & 110kV bus considering the fault level as indicated in the client provided previous ETAP study report. 26KV& 110kV bus is considered as POC (Point Of common Coupling).

The input data for all MV motors are based on the data sheets received from client.

The input data for all Transformers are based on the data sheets given by client.

The impedance parameters for all MV & LV cables are considered from default ETAP libraries and the size and length is considered based on the given information.

Table 1.1 26kV Bus Fault Level in a Grid Switch Gear - 1

KV	**Maximum fault Current**				**Minimum Fault Current**			
	3 - Phase		**1 - Phase**		**3 - Phase**		**1 - Phase**	
26	I Sym (KA)	X/R	I (KA)	X/R	I (KA)	X/R	I (KA)	X/R
	271	47.8	0.03	0.001	52	47.8	0.03	0.001

Table 1.2 110kV Bus Fault Level in a Grid Switch Gear - 2

KV	**Maximum fault Current**				**Minimum Fault Current**			
	3 - Phase		**1 - Phase**		**3 - Phase**		**1 - Phase**	
110	I Sym (KA)	X/R	I (KA)	X/R	I (KA)	X/R	I (KA)	X/R
	35.3	34.85	37.89	33.01	21.3	25.54	21.62	20.66

Table 1.3 Power Transformer Details

Description	**Quantity**	**Rated Capacity (MVA)**	**Voltage Ratio (kV)**	**%Z**
MV Transformer 26KV	2	70	26 / 14.5	14
MV Transformer 110KV	2	80	110 / 15	17
LV Transformer	2	2.5	13.8 / 0.42	6

Table 1.4 Equipment Configuration (For Power factor correction, load flow, Harmonic Analysis and Self excitation)

SI.NO	**Equipment Name / Bus**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
1	T1GKB22AP101-M01	ON	ON	ON	ON	ON	ON
2	T1GKB01AP001-M01	OFF	ON	ON	ON	OFF	OFF
3	T1GKB01AP103-M01	OFF	OFF	ON	ON	OFF	OFF
4	T1GKB01AP101-M01	OFF	OFF	OFF	ON	ON	ON
5	T1GKB01AP105-M01	ON	ON	ON	ON	ON	ON
6	T1GKB01AP005-M01	OFF	ON	ON	OFF	ON	ON
7	T1GKB01AP003-M01	OFF	OFF	OFF	OFF	ON	ON
8	T2GKB22AP102-M	ON	ON	ON	ON	OFF	OFF

	01						
9	T1GKB01AP002-M01	OFF	ON	ON	ON	ON	ON
10	T1GKB01AP102-M01	OFF	OFF	ON	ON	ON	ON
SI.NO	**Equipment Name/Bus**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
11	T1GKB01AP104-	ON	ON	ON	ON	ON	ON
	M01						
12	T1GKB01AP004-M01	OFF	ON	ON	ON	ON	ON
13	T2GKB22AP103-M01	OFF	OFF	OFF	OFF	ON	ON
14	T1GKB02AP403-M01	OFF	OFF	OFF	OFF	OFF	OFF

15	T1BBA01GS001 Bus A Incomer	ON	ON	ON	ON	ON	ON
16	T1BBA01GS001 Bus B Incomer	ON	ON	ON	ON	ON	OFF
17	T1BBB01GS001 Bus A Incomer	ON	ON	ON	ON	ON	OFF
18	T1BBB01GS001 Bus B Incomer	ON	ON	ON	ON	ON	ON
19	T1BFA01GS001-A Incomer	ON	ON	ON	ON	ON	ON
20	T1BFA01GS001-B Incomer	OFF	OFF	OFF	OFF	OFF	OFF
21	T1BFA01GS001-C Incomer	ON	ON	ON	ON	ON	ON

VI. STUDIES CASES FOR CONFIGURATION

Case-1: 2MW capacity motor at 13.8kV Bus-A and 10MW capacity motor 13.8 kV Bus-B are running along with LV loads in both switchgear 1 and 2.

Case-2: 2MW, 3MW capacity motor at 13.8kV Bus-A and 10MW, 3MW capacity motor 13.8 kV Bus-B are running along with LV loads in both switchgear 1 and 2.

Case-3: 2MW, 3MW, 10MW capacity motor at 13.8kV Bus-A and 10MW, 3MW capacity motor 13.8 kV Bus-B are running along with LV loads in both switchgear 1 and 2.

Case-4: 2MW, 3MW, 10MW, 10MW capacity motor at 13.8kV Bus-A and 10MW capacity motor 13.8 kV Bus-B are running switchgear 1. 2MW, 3MW, 10MW capacity motor at 13.8kV Bus-A and 10MW, 3MW capacity motor 13.8 kV Bus-B are running switchgear 2 along with LV loads.

Case-5: 2MW, 10MW capacity motor at 13.8kV Bus-A and 10MW, 3MW, 3MW capacity motor 13.8 kV Bus-B are running switchgear 1. 3MW, 10MW capacity motor at 13.8kV Bus-A and 10MW, 3MW, 2MW capacity motor 13.8 kV Bus-B are running switchgear 2 along with LV loads.

Case-6: MV BUS-B incomer breaker is open. MV Bus section breaker closed. 2MW, 10MW MV & LV loads are “ON” at Bus-A. 10MW, 3MW, 3MW MV & LV loads are “ON” at Bus-B in switchgear 1.

MV BUS-A incomer breaker is open. MV Bus section breaker closed. 3MW, 10MW MV & LV loads are “ON” at Bus-A. 10MW, 3MW, 2MW MV & LV loads are “ON” at Bus-B in switchgear 2.

TRV and RRRV

Maximum Transient Recovery Voltage (TRV) and Rate of Rise of Recovery Voltage (RRRV) across the capacitor bank breaker is calculated for the Opening of the breaker followed by a fault in the capacitor bank.

VII. LOAD FLOW STUDY

Load flow study, also known as power flow analysis, is an essential part of power system analysis. It is used to determine the steady-state operating condition of an electrical power system. Using ETAP, load flow analysis is performed to evaluate important system parameters such as bus voltages, real and reactive power flows, and system losses. The main objective of the load flow study is to ensure that all buses operate within acceptable voltage limits and that the system maintains a desired power factor. It also helps in identifying overloaded lines, voltage drops, and excessive losses in the network.

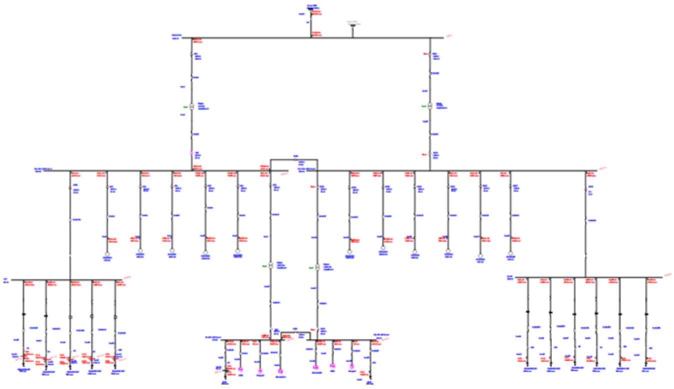


Figure 1.1 **Single Line Diagram**

SWING BUS ID	**kV**	**%MAGNITUDE**	**ANGLE**
34.5kV BUS	34.5	100	0
LOAD BUS ID	**kV**	**MW**	**Mvar**
Bus-3	13.8	0.891	0.551
Bus-5	13.8	1.876	1.163
Bus-6	13.8	1.876	1.166
Bus-7	13.8	10.876	5.294
Bus-8	13.8	10.876	5.294
Bus-20	13.8	10.876	5.294
Bus-21	13.8	10.876	5.294
Bus-22	13.8	1.876	1.159
Bus-23	13.8	1.875	1.166
Bus-24	13.8	0.891	0.551
Bus-30	13.8	0.891	0.551
Bus-42	0.48	0.012	0.025
Bus-44	0.48	0.012	0.025

Bus-45	0.48	0.009	0.012
Bus-47	0.48	0.009	0.012
Bus-49	0.48	0.667	0.500
Bus-54	0.48	0.667	0.500

To check the required power factor correction capacitor for MV and LV system and to determine the voltage profile at different buses for the scenarios.

Short Circuit Study

- Short circuit analysis is carried out to evaluate the behavior of the power system under fault conditions such as line-to-ground, line-to-line, or three-phase faults.
- It calculates the maximum fault current that can flow during different types of faults, which is critical for system design.
- This study helps in selecting appropriate circuit breakers, relays, and switchgear, ensuring they can interrupt fault currents safely.
- It verifies whether existing equipment can withstand thermal and mechanical stresses caused by faults.
- Short circuit results are used for proper protection coordination, ensuring that only the faulty section is isolated without affecting the entire system.

ID	NOMINAL kV	TYPE	SYM M.kA	ASYM M.kA	PEAK kA	M.F	X/RATIO
01 - MV - 001 A Bus A	13.8	OTHER	13.77391	22.26107	36.96738	1.616176	29.13526
01 - MV - 001 A Bus B	13.8	OTHER	15.84377	25.78179	42.74549	1.627251	32.45148
01 - PC - 001 Bus A	0.5	OTHER	26.17603	32.11753	55.62902	1.226983	4.568325
01 - PC - 001 Bus B	0.5	OTHER	26.17603	32.11753	55.62902	1.226983	4.568325
34.5kV	34.5	OTHER	10.60476	16.93651	28.20286	1.597067	24.68924

BUS							
Bus 4	13.8	OTHER	13.73087	22.02735	36.64241	1.604221	26.19864
Bus 52	13.8	OTHER	15.78701	25.4688	42.31195	1.613275	28.36856

Criteria For Analysis (Power Factor Correction)

To achieve 0.95PF at the 26kV & 110kV bus for the cases.

For high voltage switchgears originating and ending in the same plant, the allowable bus voltage range shall be 95% - 105% of nominal voltage.
For low voltage switchgears, the allowable bus voltage range shall be 95% - 105% of nominal voltage. Moreover, the end use device bus voltage range shall be 90% - 105% of nominal voltage.

Table 2.1 Power factor correction and Capacitor values

POWER FACTOR (PF) CORRECTION RESULTS AND PF CAPACITOR VALUES

CASE.NO	BUS TAG	STEADY STATE VOLTAGE (KV)	WITHOUT CAPACITOR BANK - PF	WITH CAPACITOR BANK - PF
Case-1	110kV S/S By Sub Control	110	88.3	96.13
	Gen 4 Tap off	26	88.23	96.17
	Gen 5 Tap off	26	88.14	96.14
	T1BBA01GS001 Bus A	13.8	89.64	96.98
	T1BBA01GS001 Bus B	13.8	90.07	97.15
	T1BBB01GS001 Bus A	13.8	89.64	96.99
	T1BBB01GS001 Bus B	13.8	90.1	97.14
	T1BFA01GS001-A	0.42	82.94	96.66
	T1BFA01GS001-C	0.42	82.94	96.65
	110kV S/S By Sub Contr	110	86.41	95.12

	ol			
Case-2	Gen 4 Tap off	26	86.67	95.15
	T1BBA01G S001 Bus A	13.8	98.51	97.02
	T1BBA01G S001 Bus B	13.8	98.51	97.06
	T1BBB01G S001 Bus A	13.8	99.23	97.12
	T1BBB01G S001 Bus B	13.8	99.23	97.09
	T1BFA01GS 001-A	0.42	96.51	96.65
	T1BFA01GS 001-C	0.42	97.21	96.83

Table 2.2 Bus Voltage Level Before and After PF Correction

BUS VOLTAGE RESULTS				
CASE. NO	**BUS TAG**	**STEADY STATE VOLTAGE (KV)**	**WITHOUT CAPACITOR BANK (%)**	**WITH CAPACITOR BANK (%)**
Case -1	110kV S/S By Sub Control	110	100	100
	Gen 4 Tap off	26	100	100
	Gen 5 Tap off	26	100	100
	T1BBA01G S001 Bus A	13.8	99.52	100.3
	T1BBA01G S001 Bus B	13.8	100.1	101.1
	T1BBB01G S001 Bus A	13.8	99.41	100.2
	T1BBB01G S001 Bus B	13.8	100.2	101.1
	T1BFA0	0.42	97.54	99.27
	T1BFA0	0.42	97.39	99.18
Case -2	110kV S/S By Sub Control	110	100	100
	Gen 4 Tap off	26	100	100
	T1BBA01GS001 Bus A	13.8	98.51	100.3
	T1BBA01GS001 Bus B	13.8	98.51	100.3
	T1BBB01GS001 Bus A	13.8	99.23	101.2

BUS VOLTAGE RESULTS				
CASE. NO	**BUS TAG**	**STEADY STATE VOLTAGE (KV)**	**WITHOUT CAPACITOR BANK (%)**	**WITH CAPACITOR BANK (%)**
Case-3	T1BBB01GS001 Bus B	13.8	99.23	101.2
	T1BFA0	0.42	96.51	99.21
	T1BFA0	0.42	97.21	100.1

Table 2.3 Transformer Loading and Tap Setting

TRANSFORMER LOADING AND TAP REUSLTS							
TAG		**UAT-4**	**UAT-5**	**T1ATA01GT001**	**T1ATB01GT001**	**TR3**	**TR4**
MVA Rating		70 MVA	70 MVA	80 MVA	80 MVA	2.5 MVA	2.5 MVA
Voltage Ratio		26 / 14.5 kV	26 / 14.5 kV	110 / 15 kV	110 / 15 kV	13.8 / 0.42 kV	13.8 / 0.42 kV
Case-1	% Loading	20.2	21.4	21.4	20.3	34.5	34.5
	Tap	3.75	3.75	6.25	6.25	0	0
Case-2	% Loading	44.7	-	-	39	34.5	34.5
	Tap	2.5	-	-	5	0	0

Table 2.4 Selection of Capacitor Bank Sizing

Motor Rating / LV BUS	10400 kW	2790 kW	2000 kW	LV BUS

Capacitor Power Rating (KVAR)	2973	827	569	155
Capacitor Voltage Rating (kV)	15.66	15.57	15.52	0.477
Capacitance Value (μf)	32.03	9.04	6.26	1807

Capacitance Current (A)	109.2	30.7	21.2	187.5
Inductance Value (Ω)	5.79	20.51	29.63	0.102
Inductance Current (A)	109.4	30.7	21.2	187.5

Capacitance Current

Harmonic Current flow in Capacitor % THD	0.028	0.033	0.033	0.467

Motor Starting Study

Dynamic motor starting study for the below motor is performed. The motor characteristic is modelled using ETAP parameter estimation.

Main Motor (10.4 MW).
Main Pump (2 MW).

This case considers worst possible operating scenario by modelling the minimum equivalent source short circuit level. All MV motors and LV loads are "ON".

STARTING OF MAIN MOTOR (10.4MW – T1GKB01AP103, 2MW – T2GKB22AP103)

Auto Transformer start operation is selected in ETAP and the starting voltage is adjusted to get motor terminal voltage as 64.7% in switchgear 1.

The motor can be started successfully with terminal voltage 64.7% at the motor terminal during starting (t (Start time) =17.8 Sec) in switchgear 1.

At the instant of starting, the motor the connected bus (13.8kV) voltage is observed as 92.4% in switchgear 1.

The motor can be started successfully with terminal voltage 97.3% at the motor terminal during starting (t (Start time) =2.5 Sec) in switchgear 2.

At the instant of starting, the motor the connected bus (13.8kV) voltage is observed as 96.1% in switchgear 2.

Table 2.5 Network Configuration during Motor Start.

SI.NO	Equipment Name / Bus	Status
1	T1GKB22AP101 - M01	ON
2	T1GKB01AP001 - M01	OFF
3	T1GKB01AP103 - M01	ON
4	T1GKB01AP101 - M01	ON
5	T1GKB01AP105 - M01	ON
6	T1GKB01AP005 - M01	ON
7	T1GKB01AP003 - M01	ON
8	T2GKB22AP102 - M01	ON
9	T1GKB01AP002 - M01	ON
10	T1GKB01AP102 - M01	ON
11	T1GKB01AP104 - M01	ON
12	T1GKB01AP004 - M01	ON
13	T2GKB22AP103 - M01	ON
15	T1GKB02AP403 - M01	ON

16	T1BBA01GS001 Bus A Incomer	ON
17	T1BBA01GS001 Bus B Incomer	OFF
18	T1BBB01GS001 Bus A Incomer	OFF
19	T1BBB01GS001 Bus B Incomer	ON
20	T1BFA01GS001-A Incomer	ON
21	T1BFA01GS001-B Incomer	ON

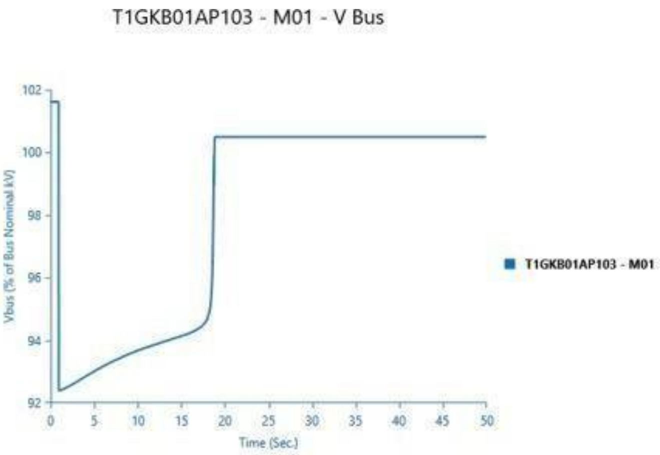


Figure 1.2 Output Characteristics of T1GKB01AP103 Motor Vbus Vs Time

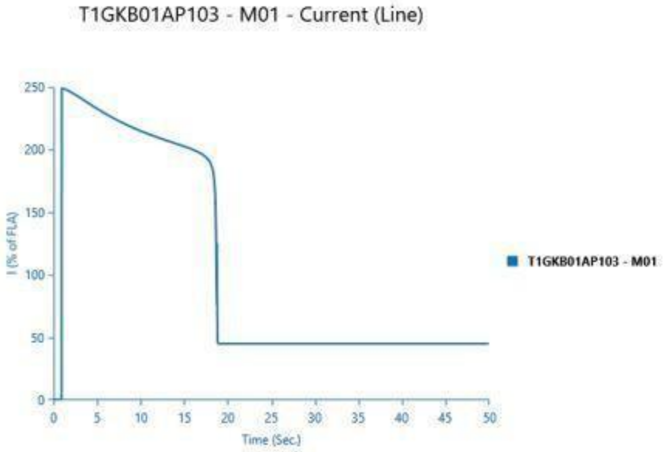


Figure 1.3 Output Characteristics of T1GKB01AP103 Motor Current (Line) Vs Time

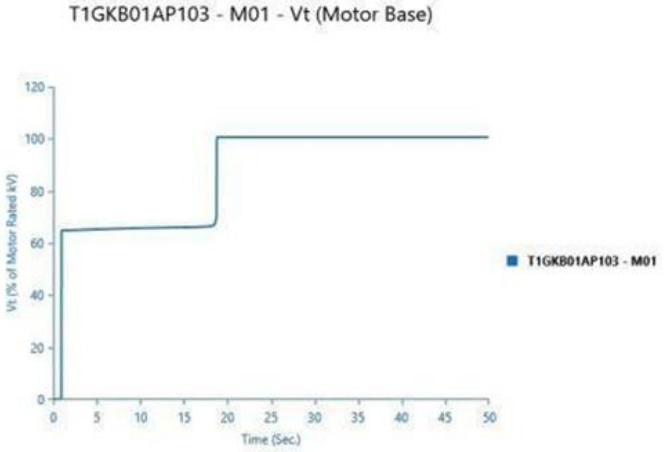


Figure 1.4 Output Characteristics of T1GKB01AP103 Motor Vt (Motor Base) Vs Time

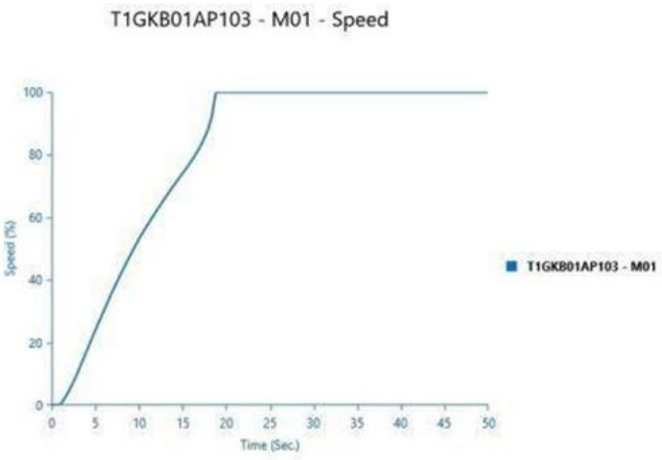


Figure 1.5 Output Characteristics of T1GKB01AP103 Motor Speed Vs Time

VIII. HARMONIC ANALYSIS STUDY

Harmonic analysis studies have been carried out based on the IEEE Std. 519-2014 guidelines. The guidelines outlined in IEEE Std. 519-2014 define the limit of harmonic currents and voltages in the overall power system..

Harmonic limits are typically evaluated at the point of common coupling (POC).In the harmonic analysis there are several important indices used to describe the effects of harmonics on the power system. The relevant harmonic indices thus need to be assessed so that these can be used for comparison with acceptable IEEE Std. 519-2014 limits to identify any system limitation and system resonance.

The IEEE Std. 519-2014 provides the limits for voltage harmonics & current harmonics. Voltage limits are based on the bus voltage level at the POC whereas the current limits vary by the ratio of short circuit current at the POC divided by the load current. It should be noted that as the ratio increases, i.e., less load current compared to fault level, higher limits are allowed.

This is due to the fact that although distortion is more, but the overall magnitude of the distorted current to the system is smaller. This will tend to have a less significant effect on the power system.

The definition of key harmonic indices analyzed to assess system performance is as summarized below:

$$V_{THD}\,(\%) = \frac{\sqrt{\sum_{h=2}^{n} V_h^2}}{V_1} \text{x } 100$$

Total Voltage Harmonic Distortion (VTHD) defined as: -

Where, “V1” is fundamental component of line voltage. “h” is harmonic order from 2 to n.

Total Current Harmonic Distortion (ITHD) defined as: -

$$I_{THD}\,(\%) = \frac{\sqrt{\sum_{h=2}^{n} I_h^2}}{I_1} \text{x } 100$$

Where, “I1” is fundamental component of line current. “h” is harmonic order from 2 to n.

The ITHD represents the total harmonic current distortion of the wave form at the particular moment (or particular load current) when the measurement is taken. It is the ratio of the rms value of harmonic current to the fundamental (non-harmonic) current measured for that load point and usually expressed as percentage. Note that the denominator used in this ratio changes with load.

Total Demand Distortion (TDD)

$$I_{TDD}\,(\%) = \frac{\sqrt{\sum_{h=2}^{n} I_h^2}}{I_1} \text{ x } 100$$

Where,“I1” is maximum demand load current (fundamental frequency current) at POC.

Total Demand Distortion (TDD) is the ratio of the rms value of the harmonic current to the maximum demand load current (full load fundamental frequency current). The full load fundamental current is the total amount of non-harmonic current consumed by all of the loads on the system when the system is at peak demand. The denominator used in this ratio does not change with load.

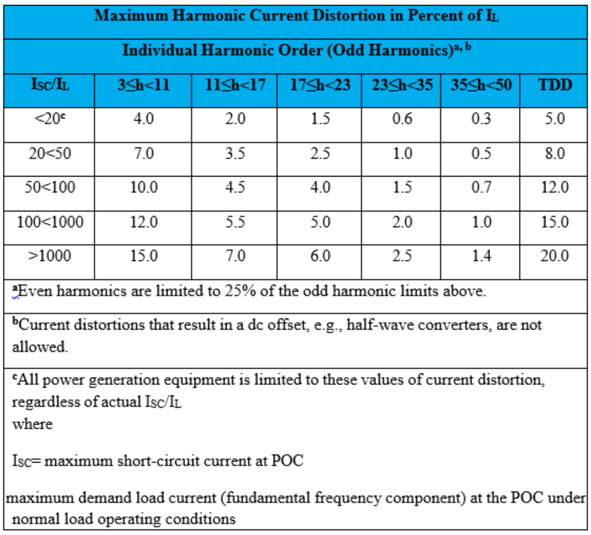
IEEE Std. 519-2014 harmonic current limits are written in terms of percentage of full load current, IL (ITDD), and not as a percentage of fundamental current, I1 (ITHD).

The following Table 6 represent the IEEE limits on allowable voltage distortion based on voltage levels & Table 6 represents IEEE limits on allowable current distortion based on load current.

Table 2.6 Voltage Distortion Limits (IEEE 519-2014 Section 5.1)

Bus Voltage at POC	**Individual Harmonic (%)**	**Total Harmonic Distortion - THD (%)**
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5[a]
[a] High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.		

Table 2.7 Current Distortion Limits for Systems Rated 120V Through 69kv (IEEE 519-2014 Section 5.2)



Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)[a, b]						
I_{SC}/I_L	**$3 \le h < 11$**	**$11 \le h < 17$**	**$17 \le h < 23$**	**$23 \le h < 35$**	**$35 \le h < 50$**	**TDD**
<20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
[a]Even harmonics are limited to 25% of the odd harmonic limits above.						
[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.						
[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L where I_{SC}= maximum short-circuit current at POC maximum demand load current (fundamental frequency component) at the POC under normal load operating conditions						

In this study, the harmonic analysis has been carried out to evaluate harmonic performance of the network and to verify that the voltage & current distortion values are within the above stated voltage and current Harmonic distortion levels. Also frequecy scan analysis was performed.

The individual harmonics of current and voltage are found to be within the limit of IEEE 519-2014. The maximum harmonic THD level (Current and voltage).

Table 2.8 Maximum THD Level

CASE	**13.8kV BUS SWG 1**					**0.42kV BUS**				
	Branch	**BUS A**		**BUS B**		**Branch**	**BUS A**		**BUS C**	
		Total Amp	**THD**	**Total Amp**	**THD**		**Total Amp**	**THD**	**Total Amp**	**THD**
C	2500 kVA primary	75.7	1.34	--	--	2500 kVA Secondary	2479	2.44	--	--
	Capacitance	123.9	0.13	163.7	0	Capacitance	462.7	2.16	462.7	2.16
	Source	337.7	0.10	90.9	0	Load	1407	3.39	140.7	3.39
C	2500 kVA primary	75.5	1.35	--	--	2500 kVA Secondary	2481	2.45	--	--
	Capacitance	123.8	0.09	162.2	0.093	Capacitance	462.3	2.14	462.3	2.14
	Sourc	731	0.0	--	--	Load	140	3.3	140	3.3

	e	.4	3				8	9	.8	9

Table 2.9 Frequency Scan Output Result

CASE	BUS ID	FREQUENCY (Hz)	IMPEDANCE (Ohms)
CASE 1	T1BBA01 GS001 Bus A	180	1.52
		240	0.85
	T1BBA01 GS001 Bus B	180	1.47
		240	0.8
	T1BBB01 GS001 Bus A	180	1.46
		240	0.9
	T1BBB01 GS001 Bus B	180	1.47
		240	0.83
	T1BFA01GS001-A	180	0.0236
		240	0.0058
	T1BFA01GS001-B	180	0.0236
		240	0.0058
	T1BFA01GS001-C	180	0.0236
		240	0.0058
	T1BBA01GS001 Bus A	180	1.42
		240	0.52
	T1BBA01GS001 Bus B	180	1.42
		240	0.52
	T1BBB01GS001	180	1.37
	BUS ID	FREQUENCY (Hz)	IMPEDANCE (Ohms)
	Bus A	240	0.54
	T1BBB01GS001 Bus B	180	1.37
		240	0.54
	T1BFA01GS001-A	180	0.0235
		240	0.0058
	T1BFA01GS001-B	180	0.0235
		240	0.0058
	T1BFA01GS001-C	180	0.0235
		240	0.0058

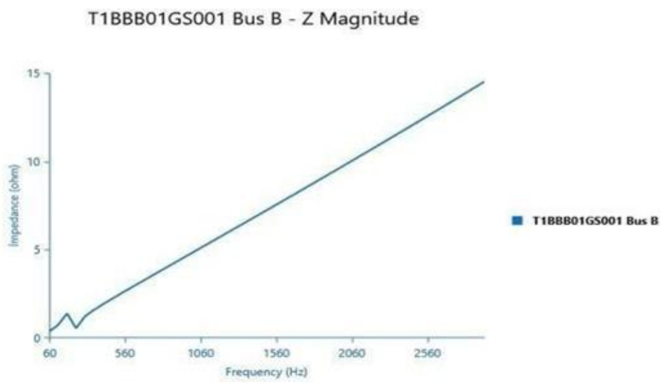


Figure 1.6 Frequency Results for T1BBB01GS001 Bus B Magnitude

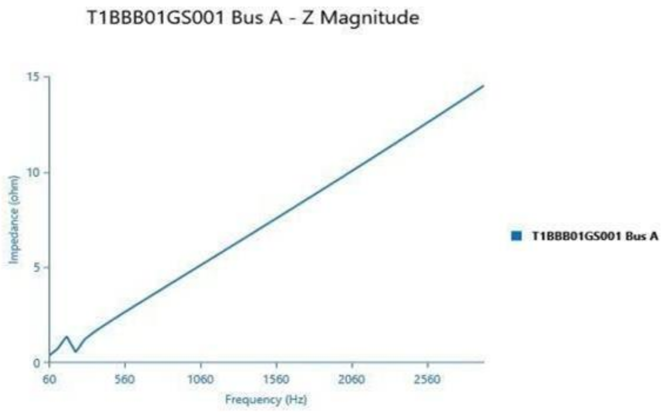


Figure 1.7 Frequency Results for T1BBB01GS001 Bus A Magnitude

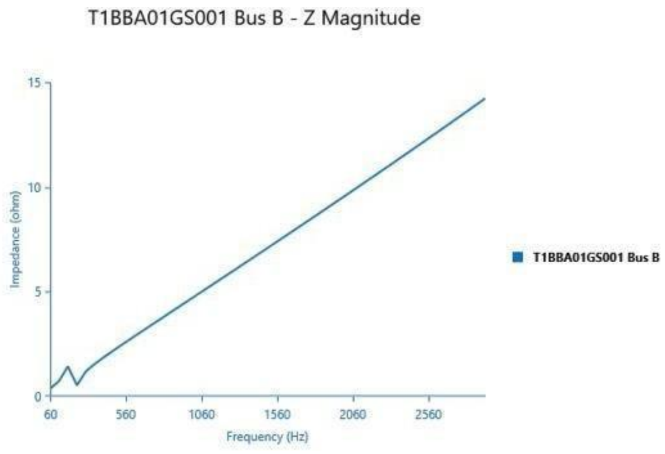


Figure 1.8 Frequency Results for T1BBA01GS001 Bus B Magnitude

IX. SELF-EXCITATION STUDY

- Self excitation is possible when the motor power factor is over compensated using power factor correction capacitors.
- All the MV Motors has been model dynamically using the information available in the data sheet.
- The cases are considered as for the self excitation study.
- Following are the sequences of operation for self excitation study
- Adapative Newton Raphson method is used with maximum iteration of 99, solution precision is 0.0001.
- Full load is considered for the respective motor.
- Total simulation time is considered as 30 seconds with time stepas 0.001.
- The 26kV & 110kV incoming circuit breakers will be tripped at 10 seconds and the respective motors (MW, Mvar, Slip, Line current) curves are plotted.

Figure 1.9 Self-Excitation Results for V Bus

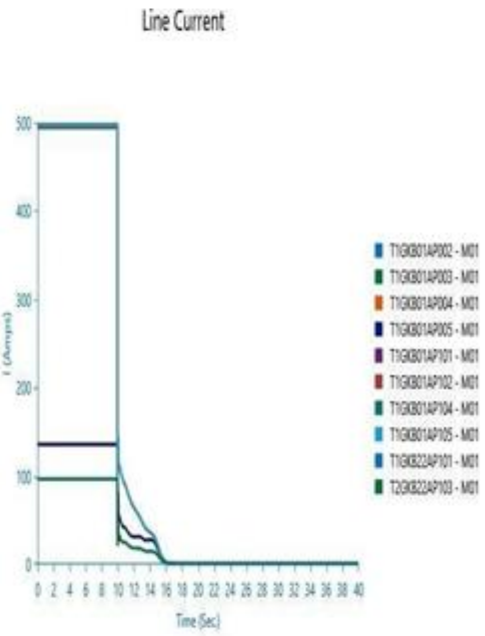


Figure 1.10 Self-Excitation Results for Line Current

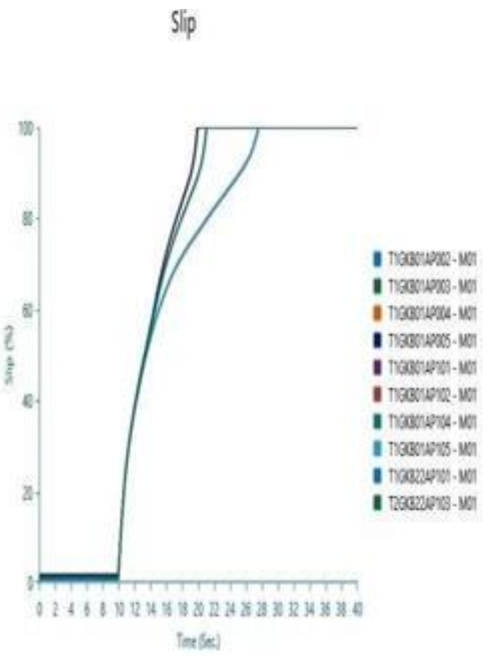


Figure 1.11 Self-Excitation Results for Slip

Power & Energy Systems, vol: 137, 107700, 2022.

X. CONCLUSION

A comprehensive analysis of the 13.8 kV power network was performed using integrated simulation studies. Load flow and short-circuit results validated voltage regulation and equipment ratings under normal and fault conditions. Motor acceleration analysis confirmed acceptable starting performance without severe voltage dips. Power factor improvement reduced reactive power demand and system losses. Transient stability studies demonstrated secure operation during disturbances. Harmonic analysis ensured compliance with power quality standards. Overall, the study provides a reliable framework for enhancing the performance and safety of medium-voltage power systems.

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