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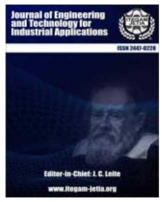

RESEARCH ARTICLE OPEN ACCESS

LOAD FLOW, SHORT CIRCUIT AND MOTOR STARTING STUDIES IN ELECTRICAL POWER SUBSTATIONS

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ABSTRACT

Power system studies are essential for the proper planning and design of electrical power substations. This paper presents the load flow, short circuit, and motor starting studies for 33/6.6/0.44 kV electrical power substation. In this paper, the load flow study calculates the active power, reactive power, and bus voltage at various locations of the substation under various operating conditions and configurations. The short circuit study evaluates the transient performance of the substation under various fault conditions such as phase-to-ground fault and three-phase-to-ground fault cases. The motor starting studies analyze the transient performance of the substation while switching the induction motors. The modeling of 33/6.6/0.44 kV electrical power substation and simulation case studies are performed in PSCAD/EMTDC software. The simulation results show the steady state and transient performance of the substation under such scenarios.

I. INTRODUCTION

Power system studies are very important for the design of electrical power substations which can be done during the planning stage. The power system simulation platform provides the opportunity to analyze the performance of the electrical power substations under steady state and transient situations by performing a variety of power system studies.

Reference [1] has presented the load flow study of a 132 kV substation in Punjab State Transmission Corporation Limited (PSTCL). The short circuit study of the 400 kV soja substation is presented in [2]. The load flow & short circuit study of the 110/20 kV substation in Romania is presented in [3-5]. The short circuit study of the Brazilian power distribution system is presented in [6]. The load flow study of the 138/69 kV substation is presented in [7]. The load flow analysis of the 132/11 kV substation in Pakistan is presented in [8]. Reference [9] has presented the load flow and short circuit study of a 220/63/30 kV substation in Algeria which is managed by managed by the Sonelgaz group's transmission network management company (GRTE). Reference [10] has presented the load flow and short circuit study of the 132/33/11 kV substation in West Bengal which is owned by West Bengal State Electricity Transmission Corporation Limited (WBSETCL). The short circuit study of the 33/11 kV Alomara substation is presented in [11]. The comparative load flow study of the 400/230 kV substation in Bangladesh is presented in [12]. The load flow and short circuit study of the electrical power distribution system in Iraq is presented in [13]. Reference [14] has presented the load flow study of a 66 kV substation in Trivandrum which is managed by Kerala State Electricity Board Limited (KSEB). The short circuit study of the 132/33 kV substation in Nigeria is presented in [15]. The load flow and short circuit study of the 132/33 kV Mawlai Nongkwar Substation is presented in [16]. The motor starting study for the substation and power plant is presented in [17-22].

In this paper, the power system studies such as load flow, short circuit, and motor starting studies are performed by considering the case study of 33/6.6/0.44 kV electrical power substation. These studies are performed in PSCAD/EMTDC software considering different operating scenarios and then the PSCAD result data are processed in MATLAB software. This paper is more related to the consulting business on power system studies which may be helpful for many power system consultants and engineers to refer to these studies.

This paper is organized as follows. Section 1 presents the importance and considerations for the load flow, short circuit, and motor starting studies. Section 2 presents the modeling of the electrical power substation considered for the case study. Section 3 presents the simulation cases, results, and analysis for the load flow, short circuit, and motor starting studies. Finally, Section 4 concludes with the important observations.

II. POWER SYSTEM STUDIES

In this section, the following power system studies are explained.

- Load flow studies.
- Short circuit studies.
- Motor starting studies.

II.1. LOAD FLOW STUDIES

Load flow is commonly referred to as power flow and it is one of the most common studies to assess the steady-state performance of the electrical power substation under various operating conditions and configurations. The objective of load flow studies is to determine the voltage, current, active, and reactive power flow, power factor, voltage drop, and losses for all the buses of the system.

Load flow studies are very important for the following requirements [23],[24]:

- Power system planning, design, and operation. It can be used to determine the optimum size of the equipment in the system.
- To determine the steady state performance under different loading conditions (start-up, minimum, normal, and maximum), and various operating configurations (generator/transmission line/load outages, tie-breaker closed, etc).
- Load flow studies are the initial condition for short circuit, transient stability, harmonic, protection coordination, and motor starting studies.
- To identify the requirement of capacitive or inductive VAR support to maintain the voltage within acceptable limits.
- To determine the transformer and load tap settings and voltage set points for the generator exciter/regulator.

The following study scenarios can be considered for the load flow studies [24]. However, it may vary depending on the configuration of the electrical power substation.

- Power generation sources can be in and out of service.
- The minimum and maximum loading conditions.
- The capacitor banks can be in and out of service.
- The outage of transformers can be considered.
- The load flow study can consider the following criteria while the engineer performs the study [23]:
- Voltage levels can be maintained as per the standard.
- The power flow of the transmission lines and transformers can be within the thermal limits.
- The reactive power limits of the generator can be maintained as per the capability curves.

II.2. SHORT CIRCUIT STUDIES

The short circuit is an abnormal connection of relatively low impedance between two points of different potentials. Hence, an overcurrent (i.e., short circuit current) will flow into the system which can damage the power system equipment. Short circuit faults can occur in the electrical power substations due to lose connection, insulation failure, aging of insulation, voltage or mechanical stress applied to the equipment, lightning strikes, wind storms, presence of animals such as birds. The short circuit studies can be used to determine the transient behavior of the electrical power substation under short circuit or fault conditions. This study helps to determine the total fault current and fault current contribution sources such as power grids, generators, and motors.

The main purpose of short circuit studies is given below [23],[25],[26]:

- To determine the maximum possible fault current which helps to determine the protective device interrupting capability.
- To design the equipment rating of new systems such as bus bars, transformers, cables, and protective devices.
- To verify the acceptable equipment rating of existing systems.
- To calculate the incident energy for arc flash studies.

The short circuit contribution mainly depends on the operating level of generations and loads, system impedance, operating configuration of electrical power substation, and transient behavior of power system components. The study scenarios for short circuit studies can be the minimum and maximum short circuit contributions and operating configurations of electrical power substations.

II.3. MOTOR STARTING STUDIES

Improper motor starting can damage the motor, create disturbance to the locally connected loads and buses, power quality issues, and service interruptions. Therefore, motor starting studies are recommended before installation. The objective of motor starting studies is to check whether the motor can be started successfully under various operating conditions. Motor starting studies are required if the motor horsepower rating exceeds 30% of the base kVA rating of the supplying transformer or 10% to 15% of the generator kVA rating if there is no transformer.

The main purpose of motor starting studies are to verify that [23],[27]:

- The motor can be started within the acceptable voltage drop and it will not affect other loads.
- The motor can be started within the acceptable start-up time.
- The speed-torque and thermal characteristics of the motor are evaluated correctly.
- The motor feeders are properly sized.
- The protection device for the motor is set properly such that the motor will not trip during start-up.
- Identifying the type and size of the starter/drive to start the motor.

The study scenario for the motor starting studies can be the minimum and maximum voltage support sources from the electrical power substation.

III. ELECTRICAL POWER SUBSTATION MODEL

The electrical power substation model considered for the case study is shown in Figure 1 and it is modeled in PSCAD/EMTDC software. In this model, the 33 kV AC network is connected to the 16 MVA, 33/6.6 kV transformers through cables and then it is connected to the 6.6 kV bus. The 6.6 kV bus is connected to the induction motor loads & capacitor banks. Also, it is connected to the 0.44 kV bus through 2 MVA, 6.6 kV/0.44 kV transformers & cables. Then, the 0.44 kV bus is connected to the lumped RL loads.

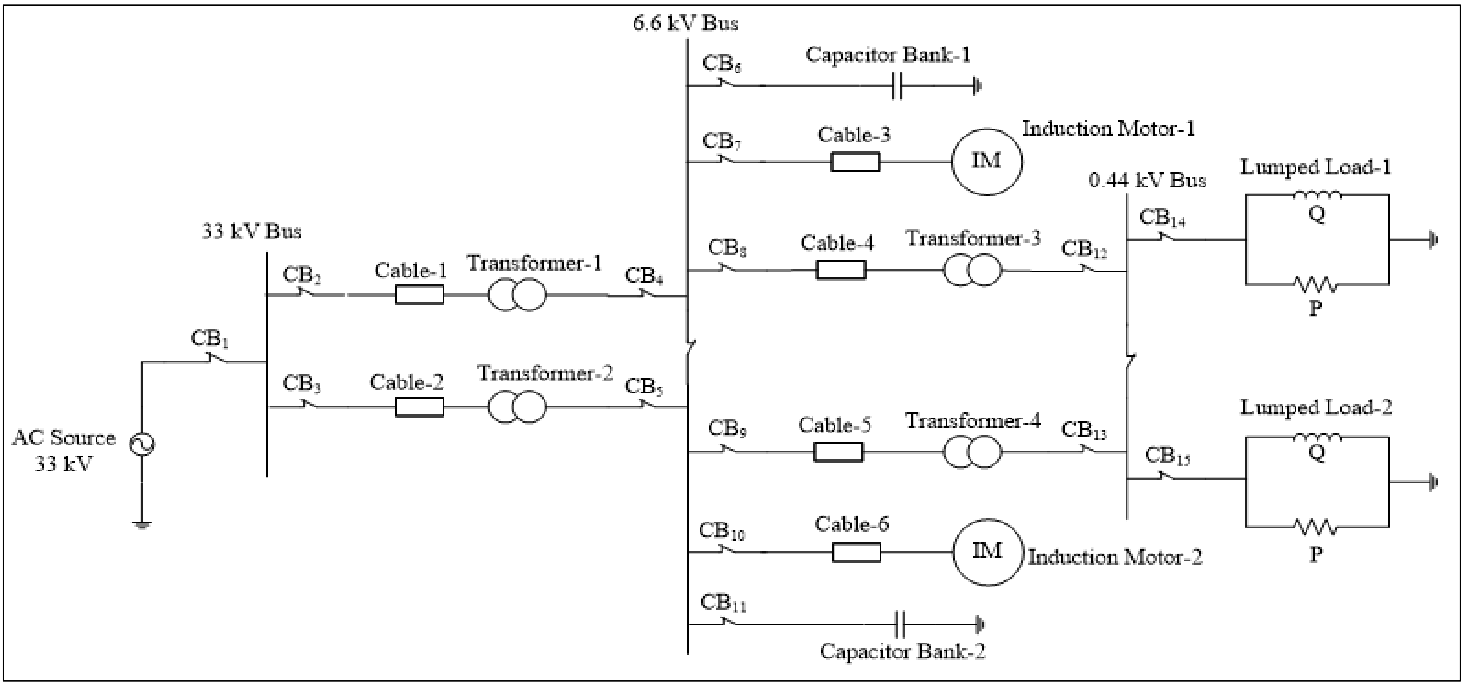


Figure 1: Electrical Power Substation Model. iFluids Engineering.
Source: Authors, (2024).

III.1. AC NETWORK & POWER TRANSFORMER MODEL

The AC network model is represented as an AC source with an equivalent short circuit MVA. The AC network impedance is represented by the impedance with an equivalent X/R ratio. The AC network parameters are listed in Table 1. The two transformers with different ratings are connected at the 33 kV and 6.6 kV buses. The transformer parameters are listed in Table 2.

Table 1: AC Network Parameters.

System Parameters	Value
Short circuit MVA	817.93 MVA
System voltage	33 kV
Source impedance (Z = R+jX)	Z = 1.69+j12.1 Ω R = 1.69 Ω & L = 38.5 mH
X/R ratio	7.147
Frequency	50 Hz

Source: iFluids Engineering, (2022).

Table 2: Transformers Parameters.

System Parameters	Transformer-1	Transformer-2
Rated MVA	16 MVA	2 MVA
Rated voltage	33/6.6 kV	6.6/0.44 kV
Impedance	6.4 %	6.25 %
Winding type	Δ/Y	Δ/Y
Frequency	50 Hz	50 Hz

Source: iFluids Engineering, (2022).

III.2. AC CABLE MODEL

The two cables are connected between the 33 kV bus and transformers. Also, the four cables are connected between 6.6 kV bus and 2 MVA transformers, and 3000 kW induction motor loads. Since all the cables are very short distance by length, the cable is represented by the equivalent impedance (i.e., resistance and reactance). The cable parameters are listed in Table 3.

Table 3: AC Cable Parameters.

System Parameters	Value
Equivalent impedance for Cable 1 & 2	0.1756+j0.2826 Ω
Equivalent impedance for Cable 3	0.0215+j0.0171 Ω
Equivalent impedance for Cable 4	0.0025+j0.0019 Ω
Equivalent impedance for Cable 5	0.003+j0.0023 Ω
Equivalent impedance for Cable 6	0.0235+j0.0187 Ω

Source: iFluids Engineering, (2022).

III.3. LOAD MODEL

The two types of loads such as induction motor loads and lumped RL loads are connected to the study substation. The induction motor loads are connected to the 6.6 kV bus. The lumped RL loads are connected to the 0.44 kV bus.

III.3.1. Induction Motor Loads

The motor loads are modeled as a squirrel cage induction motor with a rating of 3000 kW, 6.6 kV. In this motor model, the machine is set to be torque input (control) mode with slip and initial speed set to zero. The mechanical load characteristics greatly influence the starting response of the motor. The mechanical torque is directly proportional to the square of the speed. This equation is modeled and given as input to the mechanical torque of the motor. The induction motor parameters are listed in Table 4.

III.3.2. Lumped RL Loads

The lumped loads are modeled as passive loads such as resistive (R) and inductive (L) loads. The lumped loads are connected to the 0.44 kV bus. The lumped RL load parameters are listed in Table 5.

III.4. CAPACITOR BANKS MODEL

The two capacitor banks (i.e., capacitor bank-1 & capacitor bank-2) are connected at the 6.6 kV bus and the rating of the capacitor banks are 250 kVAR. The capacitor bank parameters are listed in Table 6.

Table 4: Induction Motor Parameters.

System Parameters	Value
Rated power	3000 kW
Rated voltage	6.6 kV
Frequency	50 Hz
Power factor at rated load in per unit	0.9
Efficiency at rated load in per unit	0.955
Starting current	7.1 per unit
Starting torque/Full load torque	2.9 per unit
Maximum torque/Full load torque	2.8 per unit
Number of poles	2
Moment of inertia (J)	76.3 kJ/m^2
Slip at full load	0.0083 per unit

Source: iFluids Engineering, (2022).

Table 5: Lumped Load Parameters.

System Parameters	Lumped Load-1	Lumped Load-2
Active Power & Reactive Power	287.3 kW 220.9 kVAR	154.4 kW 139.8 kVAR
Frequency	50 Hz	50 Hz
Rated voltage	415 V	415 V

Source: iFluids Engineering, (2022).

Table 6: Capacitor Banks Parameters.

System Parameters	Value
Reactive power rating	$Q_c = V^2/X_c = 250$ kVAR
Capacitor value	$C = Q_c/\omega V^2 = 18.2$ µF
Rated voltage	6.6 kV
Frequency	50 Hz

Source: iFluids Engineering, (2022).

IV. SIMULATION STUDIES

In this section, the simulation analysis for the load flow, short circuit, and motor starting studies under various operating conditions are presented.

IV.1. LOAD FLOW ANALYSIS

The load flow analysis is performed for the following cases:

- Normal Operation: Maximum Loading Conditions
- Minimum Loading Conditions: Outage of Induction Motor Loads
- Outage of Transformers

IV.1.1. Normal Operation: Maximum Loading Conditions

In this case, the load flow analysis is performed for the maximum loading conditions (i.e., with all the transformers and loads). The simulation analysis is performed for two cases such as without and with capacitor banks connected at 6.6. kV bus.

Case-1: Without Capacitor Banks at 6.6. kV Bus: In Case-1, the induction motors and lumped loads are loaded at the maximum level and the two capacitor banks are removed from the 6.6 kV bus. The active power, reactive power, bus voltage, and power factor measured at various locations of the substation are shown in Table 7. From the simulation results, it can be observed that the AC voltage at 6.6 kV bus is reduced to 6.56 kV and the AC voltage at 0.44 kV bus is also reduced due to the maximum loading of the induction motors.

Case-2: Capacitor Banks Connected at 6.6. kV Bus: In Case-2, the induction motors and lumped loads are loaded at the maximum level and the two capacitor banks are connected to the 6.6 kV bus. The active power, reactive power, bus voltage, and power factor measured at various locations of the substation are shown in Table 7. From the simulation results, it can be observed that the AC voltage at the 6.6 kV bus is reduced to 6.56 kV and the AC voltage at 0.44 kV bus is also reduced due to the maximum loading of the induction motors. The active power and power factor measured at the CB_6 and CB_{11} are equivalent to zero because these branches are connected to the capacitor banks. The power factor measured at 33 kV bus is improved due to the capacitor banks connected to the substation.

IV.1.2. Minimum Loading Conditions: Outage of Induction Motor Loads

In this case, the load flow analysis is performed for the minimum loading conditions such as the outage of two induction motor loads. The lumped loads are connected to the 0.44 kV bus. The simulation analysis is performed for two cases such as without and with capacitor banks connected at 6.6. kV bus.

Case-1: Without Capacitor Banks at 6.6. kV Bus: In Case-1, the two induction motor loads and capacitor banks are removed from the 6.6 kV bus. The active power, reactive power, bus voltage, and power factor measured at various locations of the substation are shown in Table 8. From the simulation results, it can be observed that the AC voltage at the 6.6 kV and 0.44 kV bus are improved due to the removal of induction motor loads. Also, the measurements at CB_7 and CB_{10} are not mentioned in Table 8 due to the outage of induction motor loads.

Case-2: Capacitor Banks Connected at 6.6. kV Bus: In Case-2, the induction motor loads are removed from the 6.6 kV bus and the capacitor banks are connected to the 6.6. kV bus. The active power, reactive power, bus voltage, and power factor measured at various locations of the substation are shown in Table 8. From the simulation results, it can be observed that the AC voltage at the 6.6 kV and 0.44 kV buses are improved when compared to Case-1 due to the capacitor banks. The measurements at CB_7 and CB_{10} are not mentioned due to the removal of induction motor loads. The active power and power factor measured at the CB_6 and CB_{11} are equivalent to zero because these branches are connected to the capacitor banks. Also, the power factor measured at 33 kV bus is improved.

IV.1.3. Outage of Transformers

In this case, the load flow analysis is performed for the outage of two transformers such as transformer-2 and transformer-4. The simulation analysis is performed for two cases such as without and with capacitor banks connected at 6.6. kV bus.

Case-1: Without Capacitor Banks at 6.6. kV Bus: In Case-1, the two transformers (i.e., transformer-2 and transformer-4) and capacitor banks are removed from the substation. The active power, reactive power, bus voltage, and power factor measured at various locations of the substation are shown in Table 9. From the simulation results, it can be noticed that the AC voltage at the 6.6 kV and 0.44 kV buses are reduced due to the induction motor loads. Also, the measurements at CB_3, CB_5, CB_9 and CB_{13} are not mentioned due to the outage of transformers.

Table 7: Load Flow Results for Maximum Loading Conditions.

Measurement Locations in Figure 1	Bus Voltage (kV)		Active Power (MW)		Reactive Power (MVAR)		Power Factor	
	Without capacitor banks	With capacitor banks	Without capacitor banks	With capacitor banks	Without capacitor banks	With capacitor banks	Without capacitor banks	With capacitor banks
CB_1	33	33	6.602	6.584	3.055	2.619	0.9	0.93
CB_2	33	33	3.301	3.292	1.527	1.309	0.9	0.93
CB_3	33	33	3.301	3.292	1.528	1.309	0.9	0.93
CB_4	6.554	6.56	3.303	3.294	1.304	1.089	0.93	0.94
CB_5	6.554	6.56	3.303	3.294	1.305	1.089	0.93	0.94
CB_6	-	6.56	-	-	-	0.2461	-	-
CB_7	6.554	6.56	3.008	2.998	1.089	1.119	0.94	0.94
CB_8	6.554	6.56	0.2877	0.2882	0.1955	0.1958	0.82	0.82
CB_9	6.554	6.56	0.3025	0.3031	0.2359	0.2363	0.79	0.79
CB_{10}	6.554	6.56	3.008	2.999	1.089	1.119	0.94	0.94
CB_{11}	-	6.56	-	-	-	0.2461	-	-
CB_{12}	0.4344	0.4348	0.2883	0.2888	0.1711	0.1715	0.85	0.85
CB_{13}	0.4338	0.4342	0.3031	0.3037	0.2107	0.2111	0.82	0.82
CB_{14}	0.4311	0.4315	0.222	0.2224	0.149	0.1493	0.83	0.83
CB_{15}	0.4303	0.4307	0.3628	0.3634	0.2328	0.2333	0.84	0.84

Source: Author, (2024).

Table 8: Load Flow Results for Outage of Induction Motor Loads.

Measurement Locations in Figure 1	Bus Voltage (kV)		Active Power (MW)		Reactive Power (MVAR)		Power Factor	
	Without capacitor banks	With capacitor banks	Without capacitor banks	With capacitor banks	Without capacitor banks	With capacitor banks	Without capacitor banks	With capacitor banks
CB_1	33	33	0.5857	0.587	0.775	0.2776	0.62	0.91
CB_2	33	33	0.2931	0.2937	0.3874	0.1387	0.62	0.91
CB_3	33	33	0.2926	0.2932	0.3876	0.1389	0.62	0.91
CB_4	6.591	6.598	0.2987	0.2993	0.218	0.03045	0.8	0.99
CB_5	6.591	6.598	0.2981	0.2988	0.2183	0.03021	0.8	0.99
CB_6	-	6.598	-	-	-	0.2489	-	-
CB_8	6.591	6.598	0.2909	0.2915	0.1977	0.1981	0.82	0.82
CB_9	6.591	6.598	0.3059	0.3066	0.2385	0.239	0.79	0.79
CB_{11}	-	6.598	-	-	-	0.2489	-	-
CB_{12}	0.4368	0.4373	0.2916	0.2922	0.1731	0.1734	0.85	0.85
CB_{13}	0.4363	0.4367	0.3066	0.3072	0.2131	0.2135	0.82	0.82
CB_{14}	0.4335	0.4339	0.2245	0.225	0.1507	0.151	0.83	0.83
CB_{15}	0.4327	0.4332	0.3639	0.3676	0.2355	0.236	0.84	0.84

Source: Author, (2024).

Table 10: Load Flow Results for Outage of Transformers.

Measurement Locations in Figure 1	Bus Voltage (kV)		Active Power (MW)		Reactive Power (MVAR)		Power Factor	
	Without capacitor banks	With capacitor banks	Without capacitor banks	With capacitor banks	Without capacitor banks	With capacitor banks	Without capacitor banks	With capacitor banks
CB_1	33	33	6.593	6.596	2.951	2.459	0.91	0.93
CB_2	33	33	6.593	6.596	2.951	2.459	0.91	0.93
CB_4	6.51	6.524	6.584	6.588	2.565	2.083	0.93	0.95
CB_6	-	6.524	-	-	-	0.2434	-	-
CB_7	6.51	6.524	3.006	3.006	1.083	1.085	0.94	0.94
CB_8	6.51	6.524	0.5714	0.5738	0.3979	0.3996	0.82	0.82
CB_{10}	6.508	6.521	3.006	3.007	1.083	1.085	0.94	0.94
CB_{11}	-	6.521	-	-	-	0.2432	-	-
CB_{12}	0.4286	0.4295	0.572	0.5744	0.3623	0.3639	0.84	0.84
CB_{14}	0.422	0.4229	0.2127	0.2136	0.1428	0.1434	0.83	0.83
CB_{15}	0.4179	0.4187	0.342	0.3435	0.2196	0.2205	0.84	0.84

Source: Author, (2024).

Case-2: Capacitor Banks Connected at 6.6. kV Bus**:** In Case-2, the transformers (i.e., transformer-2 and transformer-4) are removed from the substation and the capacitor banks are connected to the 6.6. kV bus. The active power, reactive power, voltage, and power factor measured at various locations of the substation are shown in Table 9. From the simulation results, it can be noticed that the AC voltage at the 6.6 kV and 0.44 kV buses are improved when compared to Case-1 due to the capacitor banks. The measurements at CB_3, CB_5, CB_9 and CB_{13} are not mentioned due to the outage of transformers. The active power and power factor measured at the CB_6 and CB_{11} are equivalent to zero because these branches are connected to the capacitor banks. Also, the power factor measured at 33 kV bus is improved.

IV.2. SHORT CIRCUIT ANALYSIS

For the short circuit analysis, the maximum short circuit contributions are considered since it is the worst-case scenario. The simulation cases are given below:

- Three-Phase-to-Ground Fault
  - Three-Phase-to-Ground Fault and Breaker Trip
- Phase to Ground Fault
  - Single Phase-to-Ground Fault and Breaker Trip

IV.2.1. Three-Phase to Ground Fault

For this case study, the presence of transformers, loads such as induction motors and lumped loads, and capacitor banks are considered. The three-phase-to-ground fault is applied at 2 sec in between CB_8 and cable-4. After the fault, the circuit breakers CB_8 and CB_{12} are opened at 2.1 sec. The fault resistance is 0.01 Ω. The response measured at 6.6 kV bus CB_8 location is shown in Figure 2.

From the simulation results, it can be observed that the peak value of the phase voltage (V_{AC}) is reduced from 5.35 kV to 0.85 kV during fault (i.e., 2 to 2.1 sec). The peak value of phase voltage is increased to 12 kV at 2.1 sec due to the switching operation of the circuit breaker and capacitor banks. The peak value of phase current (I_{AC}) is increased up to 84 kA at the first cycle and the steady state peak phase current is around 55 kA during fault. The active power (P) is increased up to 129 MW at the first spike and then the steady state oscillation around 71 MW during fault. The reactive power (Q) is varied up to 147 MVAR during the breaker trip. The reactive power is ramped down and reached the steady state value at 2.14 sec. The active power is increased to the abnormal value due to the increment of the fault current.

The response measured at the 33 kV bus CB_1 location is shown in Figure 3. From the simulation results, it can be observed that the AC voltage (V_{AC}) measured at the 33 kV bus CB_1 location is not affected due to the fault on 6.6 kV bus. The peak value of phase current (I_{AC}) is increased up to 16.58 kA at the first cycle and the steady state peak phase current is around 11.2 kA during fault. The active power (P) is increased up to 269 MW at the first spike and then the steady state oscillation around 105 MW during fault. The reactive power (Q) is increased up to 505 MVAR and then the steady state oscillation around 443 MVAR during fault. The reactive power is reached the steady state value at 2.13 sec. The active and reactive power is increased to the abnormal value due to the increment of the fault current.

Under the 3-phase-to-ground fault, the transient response of the substation is almost the same for without and with capacitor banks cases. Therefore, this paper has presented only the response of the substation with capacitor banks under the 3-phase-to-ground fault condition.

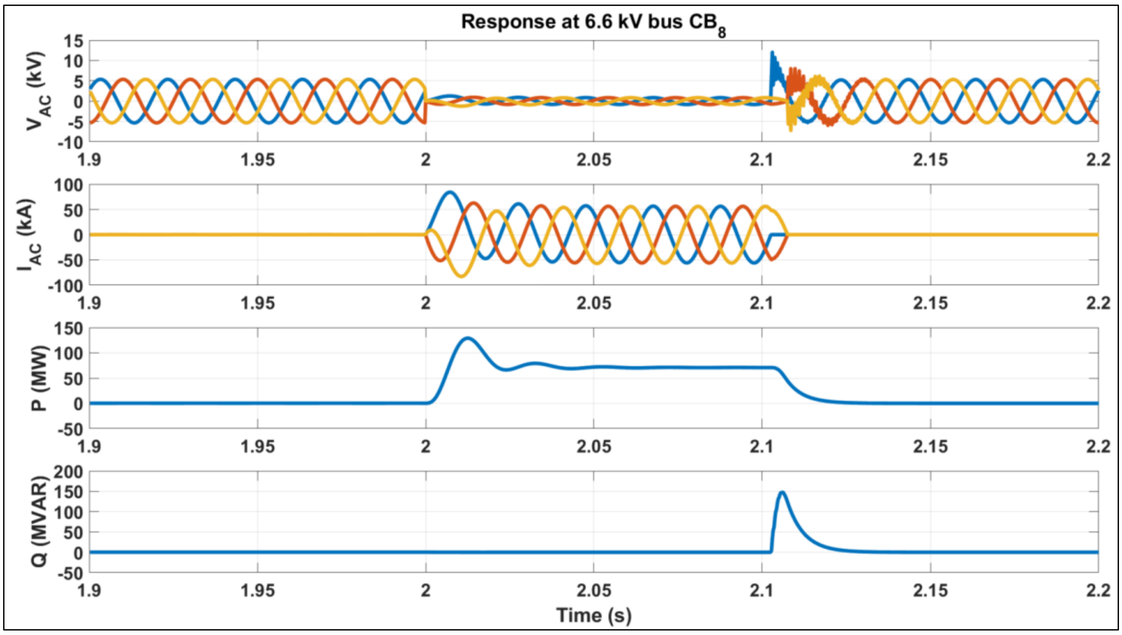


Figure 2: Response at 6.6 kV bus CB_8 location due to 3-phase-to-ground fault.
Source: Author, (2024).

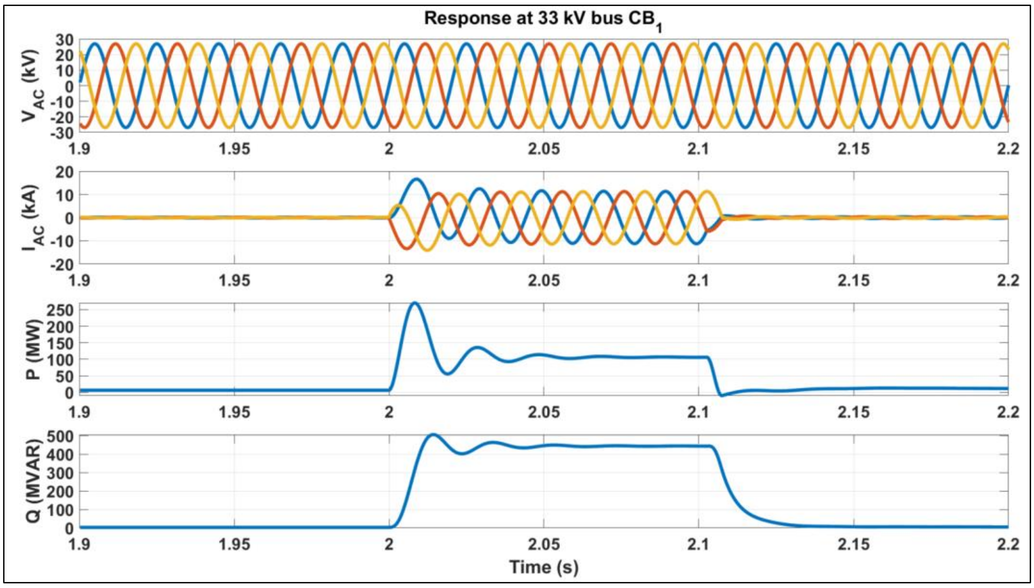


Figure 3: Response at 33 kV bus CB_1 location due to 3-phase-to-ground fault.
Source: Author, (2024).

IV.2.2. Single Phase to Ground Fault

For this case study, the presence of transformers, loads such as induction motors and lumped loads, and capacitor banks are considered. Phase A to ground fault is applied at 2 sec in between CB_8 and cable-4. After the fault, the circuit breakers CB_8 and CB_{12} are opened at 2.1 sec. The fault resistance is 1 Ω.

The response measured at the 6.6 kV bus CB_8 location is shown in Figure 4. From the simulation results it can be observed that the peak value of phase voltage (V_{AC}) is reduced from 5.35 kV to 0.94 kV during fault (i.e., 2 to 2.1 sec). At the same time, the voltage on the other 2 healthy phases is increased higher than the rated value (i.e., temporary overvoltage). The peak value of phase B voltage is increased to 8.35 kV and the peak value of phase C voltage is increased to 8.58 kV. The peak value of phase current (I_{AC}) is increased up to 1.1 kA at the first cycle and the steady state peak phase current is around 0.978 kA during fault. The active power (P) is increased up to 0.87 MW and the reactive power (Q) is increased up to 0.9 MVAR during fault. The active and reactive power is reached the steady state value at 2.136 sec.

The response measured at the 33 kV bus CB_1 location is shown in Figure 5. From the simulation results, it can be observed that the AC voltage (V_{AC}) measured at the 33 kV bus CB_1 location is not affected due to fault on the 6.6 kV bus. The peak value of phase A current (I_{AC}) is increased to 0.24 kA and the peak value of phase B current is also increased to 0.27 kA during fault. The active power (P) is increased up to 9.85 MW and the reactive power (Q) is increased up to 3 MVAR during fault. The active and reactive power is reached the steady state value around 2.125 sec.

Under the single-phase to ground fault condition, the transient response of the substation is almost the same for without and with capacitor banks cases. Therefore, this paper has presented only the response of the substation with capacitor banks under the 1-phase to ground fault condition.

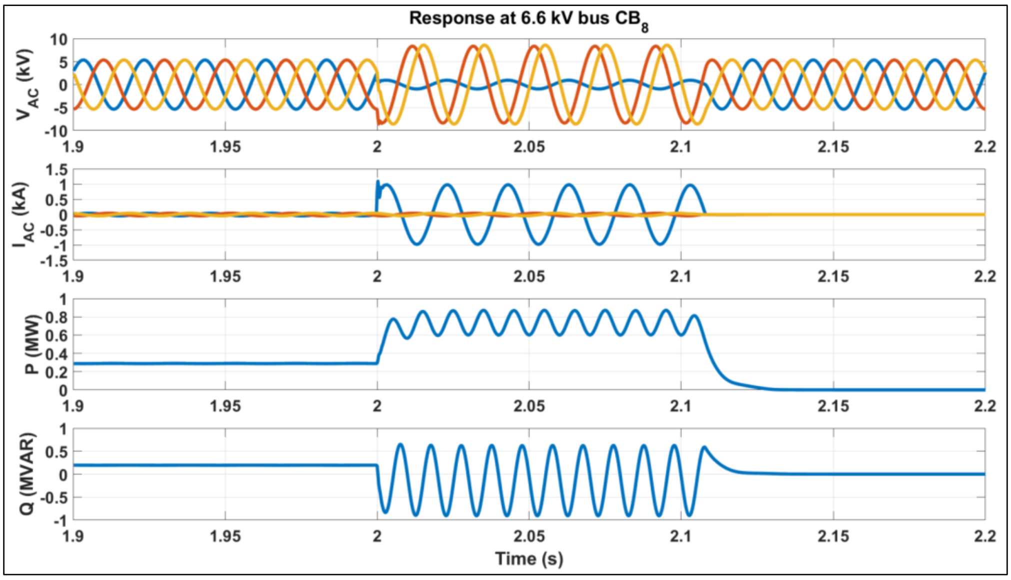


Figure 4: Response at 6.6 kV bus CB_8 location due to phase A to ground fault.
Source: Author, (2024).

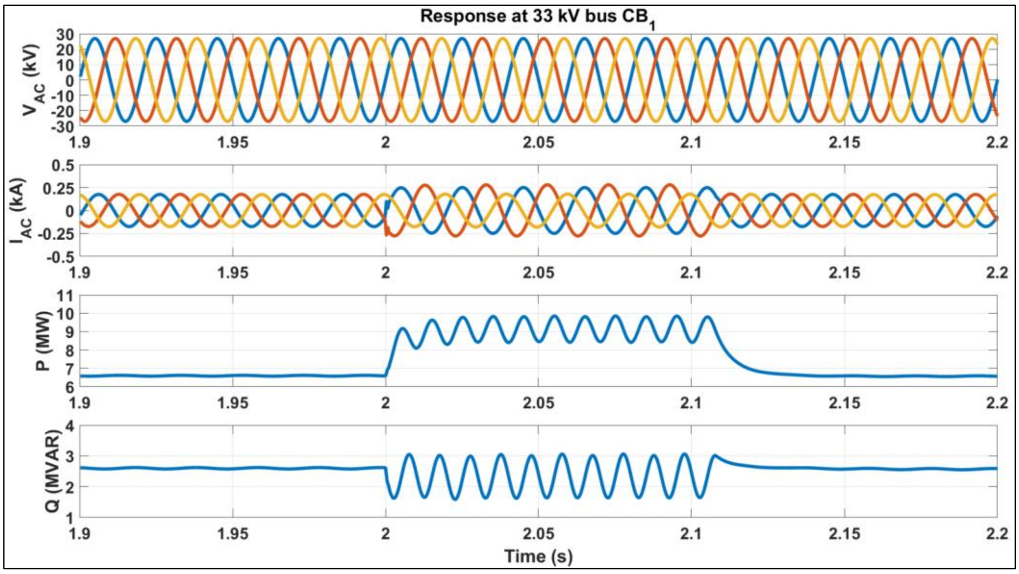


Figure 5: Response at 33 kV bus CB_1 location due to phase A to ground fault.
Source: Author, (2024).

IV.3. MOTOR STARTING ANALYSIS

For the motor starting analysis, the response of the substation is analyzed under the starting of one and two induction motor loads. The simulation cases are given below:

- Starting of induction motor 1
- Starting of induction motors 1 and 2

IV.3.1. Starting of Induction Motor-1

In this case, the performance of the substation is analyzed under the starting operation of induction motor-1 (CB_7 branch). For this study, the presence of AC source, transformers, transmission lines, and lumped loads are considered. Also, the capacitor bank-1 at branch CB_6 is connected to the substation. The induction motor-2 at branch CB_{10} and the capacitor bank-2 at branch CB_{11} are removed from the substation. The induction motor-1 is started at 1 sec by closing the circuit breaker CB_7. The response of the substation due to the start-up of induction motor-1 is shown in Figure 6.

Figure 6 (a) shows the response measured at the 6.6 kV bus CB_7 location. During motor start-up, the line-to-line RMS voltage (V_{rms}) is reduced from 6.6 kV to 6.3 kV and the RMS current (I_{rms}) is increased to 2.08 kA. The active power (P) measured at CB_7 is increased to 13.16 MW and the reactive power (Q) is varied to 19.53 MVAR. The line-to-line RMS voltage, RMS current, active and reactive power are recovered back to the steady state value at around 2.25 sec.

Figure 6 (b) shows the response of induction motor-1 during start-up. The electrical torque (T_e) is increased up to 5.8 per unit with an oscillatory transient. The mechanical torque (T_m) and speed (ω) are increased in a ramp manner and reached the steady state at around 2.25 sec.

Figure 6 (c) shows the response measured at the 33 kV bus CB_1 location. The line-to-line RMS voltage (V_{rms}) at the 33 kV bus is not affected due to the motor start-up at the 6.6 kV bus. But the RMS current is increased to 0.428 kA, the active power (P) is increased to 13.98 MW, and the reactive power (Q) is increased to 21.12 MVAR. Therefore, the AC current, active and reactive power at 33 kV bus has been affected significantly due to induction motor-1 starting at 6.6 kV bus.

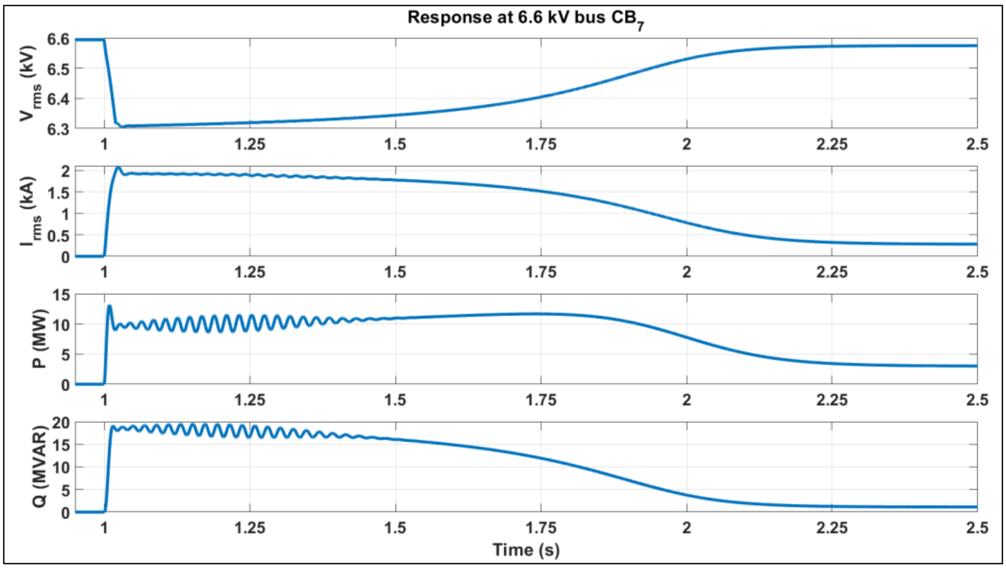
IV.3.2. Starting of Induction Motor 1 and 2

In this case, the performance of the substation is analyzed during the starting operation of induction motor-1 (CB_7 branch) and induction motor-2 (CB_{10} branch). For this study, the presence of AC source, transformers, transmission lines, lumped loads, and capacitor banks are considered. Also, the capacitor bank-1 at branch CB_6 and capacitor bank-2 at branch CB_{11} are connected to the substation. The induction motor-1 and induction motor-2 are started at 1 sec by closing the circuit breakers CB_7 and CB_{10}. The response of the substation due to the start-up of induction motor load-1 and induction motor load-2 is shown in Figure 7.

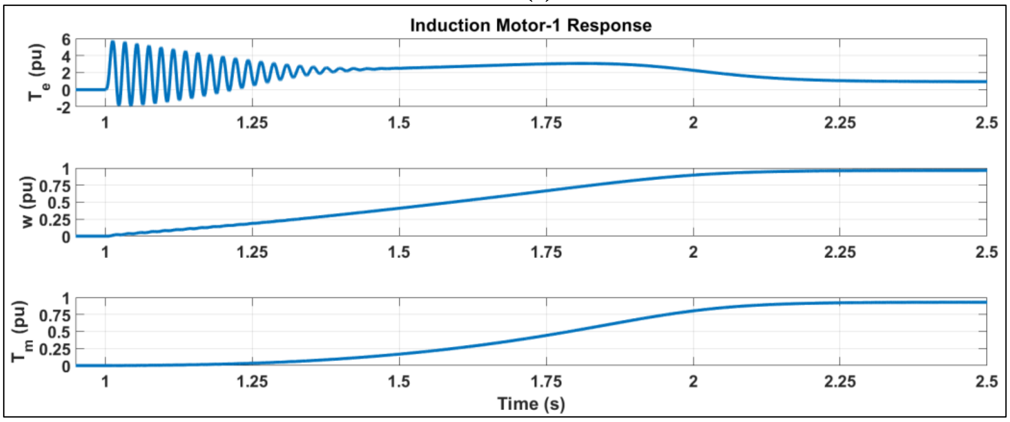
Figure 7 (a) & (c) shows the response measured at the 6.6 kV bus CB_7 & CB_{10} location. During motors 1 & 2 start-up, the line-to-line RMS voltage (Vrms) is reduced from 6.6 kV to 6.044 kV and the RMS current (Irms) is increased to 2.003 kA. The active power (P) is increased to 12.37 MW, and the reactive power (Q) is varied to 17.99 MVAR. The line-to-line RMS voltage, RMS current, active and reactive power are recovered back to the steady state value at around 2.4 sec. Figure 7 (b) & (d) shows the response of the induction motors 1 & 2 during start-up. The electrical torque (Te) is increased up to 5.41 per unit with an oscillatory transient. The mechanical torque (Tm) and the speed (ω) are increased in a ramp manner and reached the steady state at around 2.25 sec. Also, the transient response measured at 6.6 kV bus CB_7 and CB_{10} are almost the same.

Figure 7 (e) shows the response at the 33 kV bus CB_1 location. The line-to-line RMS voltage (V_{rms}) at the 33 kV bus is not affected due to the motors 1 & 2 start-up at the 6.6 kV bus. But the RMS current is increased to 0.8 kA, the active power (P) is increased to 26.18 MW, and the reactive power (Q) is varied to 40.16 MVAR. Therefore, the AC current, active and reactive power at 33 kV bus has been affected significantly due to motors 1 & 2 starting at 6.6 kV bus.

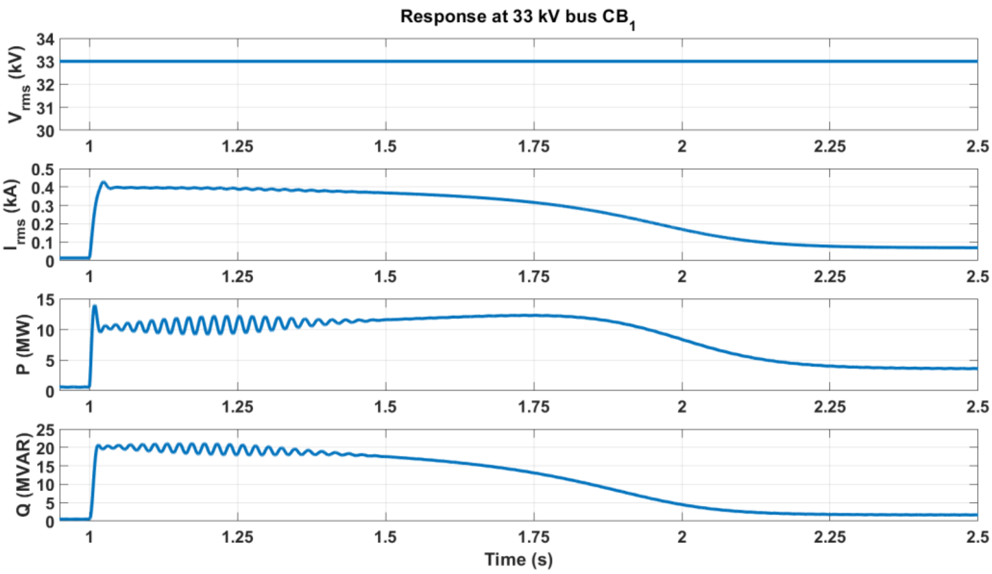
If the two induction motors are started at different times, the transient response (i.e., AC current, active and reactive power) at 33 kV bus is similar to the previous case shown in Figure 6. If the two motors are started at the same time, then the transient response at 33 kV bus is increased twice when compared to the previous case.



(a)

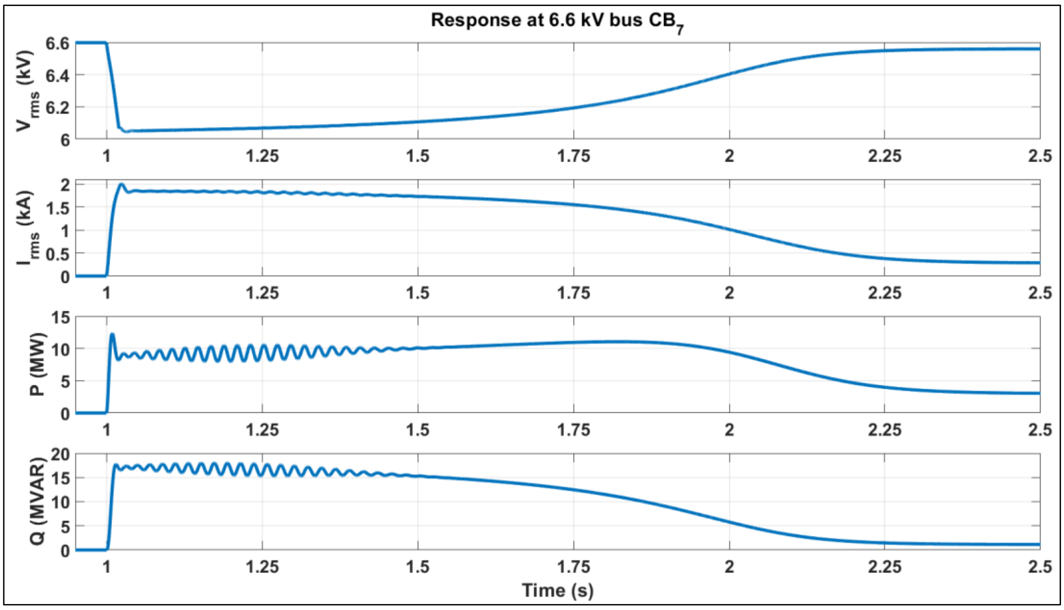


(b)

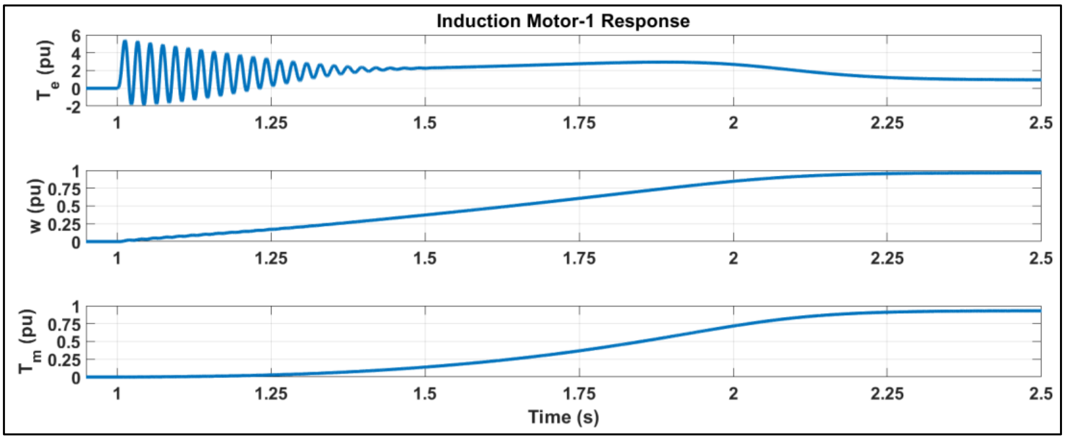


(c)

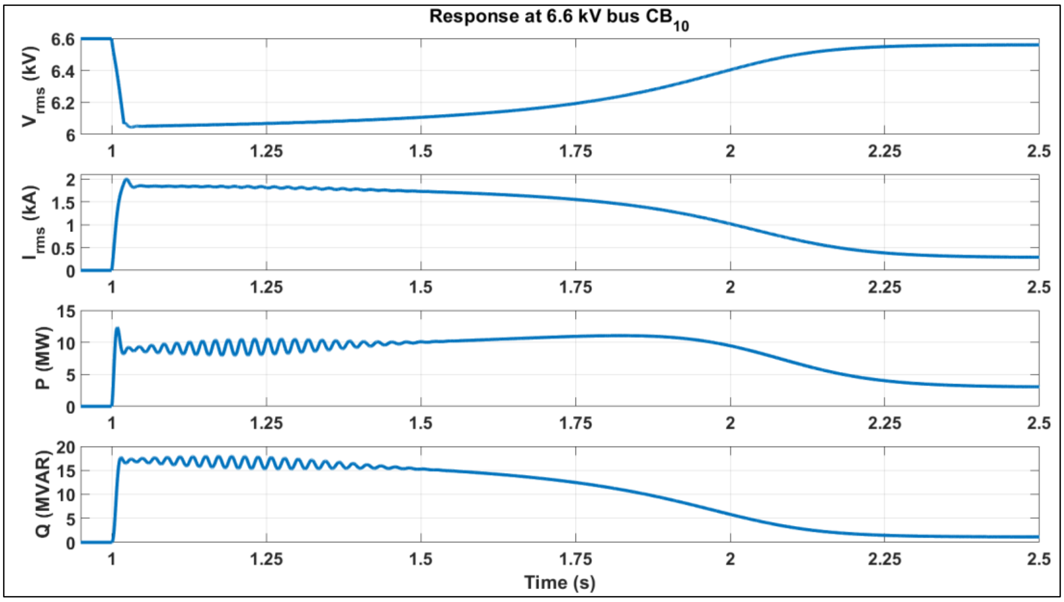
Figure 6: Response of substation during induction motor-1 start-up. (a) Response at 6.6 kV bus CB_7 location, (b) Induction motor-1 response, (c) Response at 33 kV CB_1 location.
Source: Author, (2024).


Response at 6.6 kV bus CB7
Vrms (kV)
Irms (kA)
P (MW)
Q (MVAR)
Time (s)

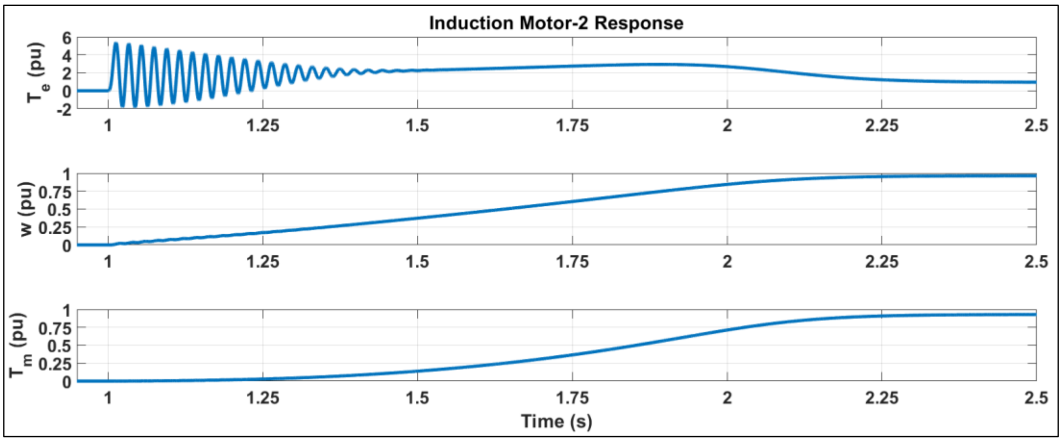
(a)


Induction Motor-1 Response
Te (pu)
w (pu)
Tm (pu)
Time (s)

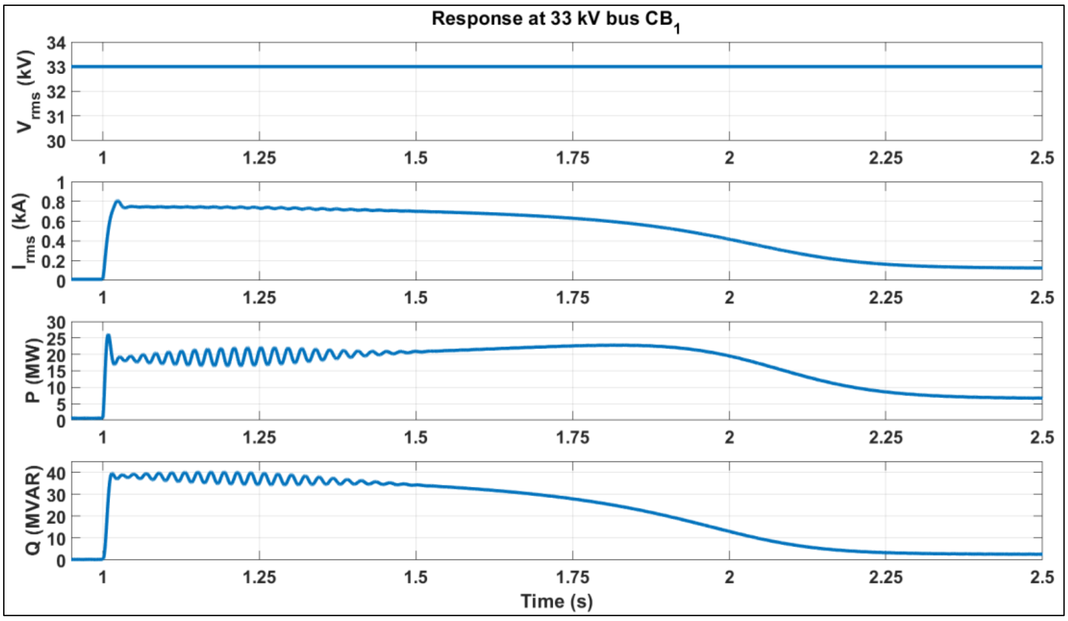
(b)


Response at 6.6 kV bus CB10
Vrms (kV)
Irms (kA)
P (MW)
Q (MVAR)
Time (s)

(c)



(d)



(e)

Figure 7: Response of substation during induction motors 1 & 2 start-up. (a) Response at 6.6 kV Bus CB_7 location, (b) Induction motor-1 response, (c) Response at 6.6 kV Bus CB_{10} location, (d) Induction motor-2 response, (e) Response at 33 kV CB_1 location.
Source: Author, (2024).

V. CONCLUSIONS

In this paper, the load flow, short circuit, and motor starting studies for the 33/6.6/0.44 kV electrical power substation are presented. The observations from those studies are given below:

- The load flow analysis is performed for the maximum and minimum loading and transformer outage conditions considering both without and with capacitor banks. From the simulation results, it can be observed that the AC voltage at 6.6 kV and 0.44 kV buses are reduced due to the induction motors and lumped loads. Also, the power factor at the 33 kV terminal is improved due to the presence of capacitor banks at the 6.6 kV bus.

- The short circuit analysis is performed for the three-phase-to-ground fault and single-phase-to-ground fault cases. From the results, it can be noticed that the fault current, active power, and reactive power at 33 kV and 6.6 kV bus are increased to the abnormal value during three-phase-to-ground fault. The single-phase-to-ground fault has produced temporary overvoltage on the other two healthy phases. However, the single phase-to-ground fault has less impact on the transient response of the fault current, active power, and reactive power.

- The motor starting analysis is performed for the starting of single and double induction motor load cases. From the results, it can be observed that the starting of the induction motor load has a significant impact on the transient response of the AC current, electrical torque, active power, and reactive power at 6.6 kV and 33 kV bus. Also, the transient response of AC current, active power, and reactive power at 33 kV bus has been doubled when the two induction motors are started at the same time.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Mohan Muniappan.
Methodology: Mohan Muniappan.
Investigation: Mohan Muniappan.
Discussion of results: Mohan Muniappan.
Writing – Original Draft: Mohan Muniappan.
Writing – Review and Editing: Mohan Muniappan.
Resources: Mohan Muniappan.
Supervision: Mohan Muniappan.
Approval of the final text: Mohan Muniappan
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