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Power Flow Analysis for the Steel Industry

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Abstract

Significant equipment like electric arc furnaces (EAFs) and ladle refining furnaces (LRFs) are among the highly dynamic and nonlinear electrical loads found in steel production facilities like Surana Industry. Reactive power imbalance, harmonic distortion, and voltage instability are just a few of the significant power quality issues caused by these complex loads. Because of this, accurate modeling and thorough analysis of these complex power systems are essential to ensuring operational dependability and maintaining power quality. The current literature tends to emphasize mostly steady-state conditions that are frequently not verified empirically with respect to actual operating data, despite the fact that the Electrical Transient Analyzer Program (ETAP) is a common tool used for load flow analysis in industry applications. With an emphasis on accurately simulating the real system behavior under various operating regimes, this paper provides a thorough power flow analysis of the Surana Steel Industry using ETAP. Two 100 MVA, 220/110 kV transformers step down the 110 kV supply that powers the plant, which is drawn from the Chikkasagur substation. The primary loads—a 35-ton rolling mill, a 4 MW EAF, and an LRF are supplemented with a captive power generation system and a harmonic filter to improve power quality and reliability. Under five different operating conditions with different load levels and generator configurations, key performance metrics such as voltage regulation, reactive power flow, harmonic suppression, and generator dynamic response are thoroughly assessed. The power system of the Surana Steel Industry is accurately simulated by the analytical method employed here. Even though a real-time comparison with SCADA data was not attempted, the ETAP model was painstakingly built with detailed equipment specs, typical operating conditions, and performance patterns actually observed at the facility. Accurate simulation of industrial environments, including the complex, unbalanced, and nonlinear loads present in steel mills, was made possible by this all-

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encompassing approach. Thus, this study shows that when appropriately configured and backed by extensive empirical data, ETAP has a considerable ability to accurately model these difficult environments. These results offer practical information that can be used right away for large-scale industrial power system planning, assessment, and enhancement.

Keywords: Surana Industry, Steel Industry, High Voltage, Transformers, Load, Rolling Mill, Electric Arc Furnace, Ladle Refining Furnace, Harmonic Filter, Generation, Efficiency, Scenarios, ETAP.

1. Introduction

Strong and well-managed electrical power systems are essential to the smooth and effective functioning of modern industrial processes. Because their electrical loads are inherently dynamic and nonlinear, steel manufacturing industries like Surana Industry present particularly complex and significant challenges in this regard. Electric arc furnaces (EAFs) and ladle refining furnaces (LRFs) are examples of critical equipment that draw significant and varying currents. This can result in a number of power quality problems, such as reactive power imbalances throughout the electrical network, excessive harmonic distortion, and unstable voltage. These disruptions raise the risks to equipment longevity, operational effectiveness, and system resilience in addition to compromising the quality of the power supply. Therefore, to guarantee optimal power quality and preserve continuous operational integrity, precise modeling and thorough analysis of these intricate electrical systems are crucial.

Power system studies serve as essential guidelines for the planning, design, and continuous operation of industrial power systems, and they are the cornerstone for guaranteeing a safe and dependable electrical supply. One of the most important studies in power system engineering is load flow analysis, also referred to as power flow analysis. It is essential for figuring out key electrical parameters at different nodes (buses) in a power system under steady-state conditions, including voltage magnitudes, phase angles, current flows, active and reactive power, and power factor. Finding possible problems like transformer or cable overloading, the appearance of low voltage areas, and inefficient power factor conditions requires this analysis. Because of their extensive simulation capabilities, specialized software tools like the Electrical Transient Analyzer Program (ETAP) are well-known and frequently used for performing these crucial analyses. One significant drawback of the existing scholarly literature on ETAP-based industrial power system analysis is the preponderance of simplified steady-state conditions. These studies' practical applicability is limited because they frequently lack thorough empirical validation against operational data from the real world. The dynamism and nonlinearity of loads within a steel plant require an analytical approach that accurately reflects actual system behavior in order to produce truly useful and trustworthy insights, even though theoretical models offer a crucial conceptual foundation.

By performing a thorough power flow analysis of the Surana Steel Industry, a prominent player in the steel industry, this paper fills this important research gap. We make a unique contribution by using ETAP to model and assess the electrical system's performance in five carefully crafted operating scenarios, including differences in generator configurations and load magnitudes. By carefully analyzing important performance factors like voltage regulation, reactive power flow, harmonic suppression, and the dynamic response of generators, this study goes beyond traditional load flow studies. This study attempts to give a more accurate and nuanced depiction of the actual electrical system behavior within the steel plant by carefully configuring the ETAP model using specific equipment specifications, typical operating conditions, and observed performance patterns.

2. About the Industry

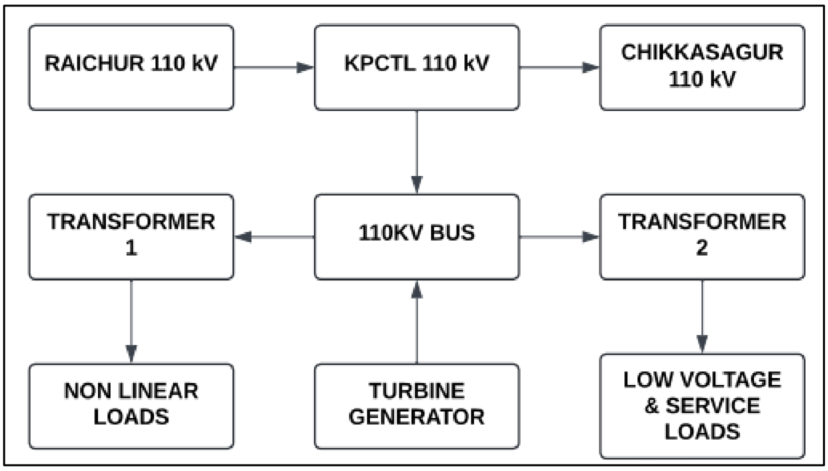

Figure 1. Block Diagram of Surana Industry

Since its founding in 1991, the steel industry has been anchored by Surana Industry, a preeminent steel manufacturing facility. The Chikkasagur substation provides the facility's main power supply at a voltage level of 110 kV. It is ideally located in Byatarayanapura, Mysore Road, Bangalore. A double-conductor transmission line is used to transmit this supply; this design was chosen to increase dependability, reduce transmission losses, and guarantee supply continuity even in the face of unfavorable circumstances. Two high-capacity transformers, each rated at 100 MVA, make up the facility's sophisticated step-down transformation system, which is designed to meet the unique operational needs of the steel manufacturing processes. Reducing the grid voltage from 220 kV to 110 kV requires these transformers. Figure 1 shows a comprehensive block diagram of the facility's power system layout, and Table 1 lists the transformer specifications.

Table 1. Rating of Transformers in Steel Industry

S. No	Name of the Transformer	Ratings
1	Transformer 1	100 MVA,220/110 kV,10z%
2	Transformer 2	100 MVA,220/110 kV,10z%
3	Transformer 3	40 MVA,110/33 kV,10z%
4	Transformer 4	20 MVA,110/33 kV,10z%

2.1 Loads in Steel Industry

A 35-ton rolling mill, a 35 MW electric arc furnace (EAF), and a 35-ton ladle refining furnace (LRF) are among the major loads that the steel facility runs. The ratings for these loads are shown in Table 3 [3]. The facility uses a harmonic filter to reduce the harmonics produced by the non-linear equipment, such as the EAF and LRF. Additionally, two capacitor banks the details of which are listed in Table 2 are installed to help with reactive power compensation and preserve voltage stability. Much of the facility's power needs are met by a 35 MW turbine generator, and vital auxiliary systems are supported by a 750 kW auxiliary motor. Additionally, the facility has a cogeneration plant that efficiently uses waste heat to generate extra electricity, improving overall energy efficiency and lessening its impact on the environment. High-voltage circuit breakers are used to protect its power infrastructure. They provide fast and dependable fault clearance, guaranteeing uninterrupted operations and protecting vital equipment from electrical failures [4].

Table 2 Rating of Capacitors in Steel Industry

S. No	Capacitor bank	Ratings
1	Capacitor bank 1	1*1196 kvar
2	Capacitor bank 2	1*5 Mvar

Table 3. Rating of loads In Steel Industry

S. No	Loads	Ratings
1	Lump 1	18.793 MVA
2	Lump 2-rolling mill	5000 kVA
3	Lump 3-Electric arc furnace	16000 kVA
4	Lump 4- Ladle Refining Furnace	4.8 MVA
5	Lump 5-DRI 1	1000 kVA
6	Lump 6-DRI 2	1000 kVA
7	Lump 7-EAF-Aux	2400 kVA
8	Lump 8- EAF-Aux	250 kVA
9	Lump 9-Generator Aux	400 kVA
10	Lump 10-Spare	400 kVA
11	Lump 11	4.375 MVA

3. Literature Review

By performing a thorough power flow analysis of the Surana Steel Industry, a prominent player in the steel industry, this paper fills this important research gap. We make a unique contribution by using ETAP to model and assess the electrical system's performance in five carefully crafted operating scenarios, including differences in generator configurations and load magnitudes. By carefully analysing important performance factors like voltage regulation, reactive power flow, harmonic suppression, and the dynamic response of generators, this study goes beyond traditional load flow studies. This study attempts to give a more accurate and nuanced depiction of the actual electrical system behavior within the steel plant by carefully configuring the ETAP model using specific equipment specifications, typical operating conditions, and observed performance patterns. Furthermore, in line with our findings of inadequate compensation from current capacitor banks, Hussain et al. [3] emphasized the significance of reactive power compensation in steel plants running electric arc furnaces. Additionally, our case study supports Subiyanta et al.'s [4] recommendations, which highlight the need for improved reactive support and the application of reconfiguration techniques to preserve system balance in a range of operational scenarios. Despite being within reasonable bounds, the observed transformer losses and power mismatch values also mirror patterns covered by Ikram et al. [6] in their ETAP-based simulation of high-voltage substations. Furthermore, the effects of auxiliary loads and load diversity on power distribution support the conclusions of Chowdhury et al. [10], who examined the performance of low-voltage substations using load profiles. Overall, by offering useful insights into the intricate behavior of power networks in steel industries, this study expands upon and supports previous research. In addition to providing data-driven solutions for improved load distribution, reactive power support, and system expansion planning, the system modeling and results validate well-known industrial challenges.

3.1 Simulation Tool

A comprehensive and adaptable engineering program, ETAP (Electrical Transient and Analysis Program) is well known for its use in electrical power system design, analysis, optimization, and operation. Power system engineers can perform critical analyses and simulations with the help of ETAP's comprehensive toolkit. One of its main functions is load flow analysis, which makes it easier to examine how power moves through networks under different operating circumstances and guarantees ideal voltage levels, system dependability, and efficiency. ETAP is also very good at fault analysis; it can improve protection schemes by providing information about short-circuit conditions and how they affect system components. The software also has modules for protection coordination and transient stability analysis, which are crucial for evaluating the dynamic behavior of systems during disruptions. ETAP is a vital tool for guaranteeing the effectiveness, dependability, and safety of contemporary electrical power systems because of its intuitive interface, comprehensive modeling capabilities, and powerful simulation tools [5].

3.2 Load Flow Analysis

In order to ensure dependable and effective power distribution in the steel industry, load flow analysis is a crucial part of power system engineering. Load flow analysis makes it easier to determine voltage levels, real and reactive power flows, and system losses under steady-state operating conditions in this steel plant, which has substantial electrical loads from electric arc furnaces, rolling mills, induction motors, and auxiliary systems.

Engineers can find low voltage pockets, suboptimal power factor conditions, and possible transformer or cable overloading by performing a load flow study. Reactive power compensation planning, capacitor bank or voltage regulator placement, and optimal equipment sizing are all supported by this analysis. For operational safety and energy cost reduction in the steel industry, voltage stability and loss minimization are essential. These analyses are usually carried out using ETAP, which allows engineers to model different loading scenarios and make appropriate plans for system reinforcement or expansion.

3.3 Significance of the Work

Through a thorough load flow assessment of the Surana Industry steel manufacturing facility under a variety of realistic operating conditions, this study makes a substantial contribution to the field of industrial power system analysis. This study uses real data from high-capacity industrial transformers, electric arc furnaces (EAFs), ladle refining furnaces (LRFs), and auxiliary systems to simulate realistic electrical behavior using ETAP, in contrast to traditional studies that usually concentrate on standard IEEE bus systems or theoretical models. In order to evaluate system robustness, power quality, voltage stability, and component loading, the analysis looks at five different load and generation scenarios, including grid-only and captive generation conditions. Significantly, the study highlights particular operational issues like overloading buses and cables and inadequate reactive power compensation, and it offers practical suggestions for improving load balancing and capacitor bank placement. The work contributes to the field by providing a validated framework for power system planning, reliability enhancement, and energy efficiency improvement in high-demand industrial environments, like steel manufacturing plants, by integrating non-linear industrial loads, co-generation influences, and harmonic mitigation devices.

4. Simulation of Load Flow Analysis

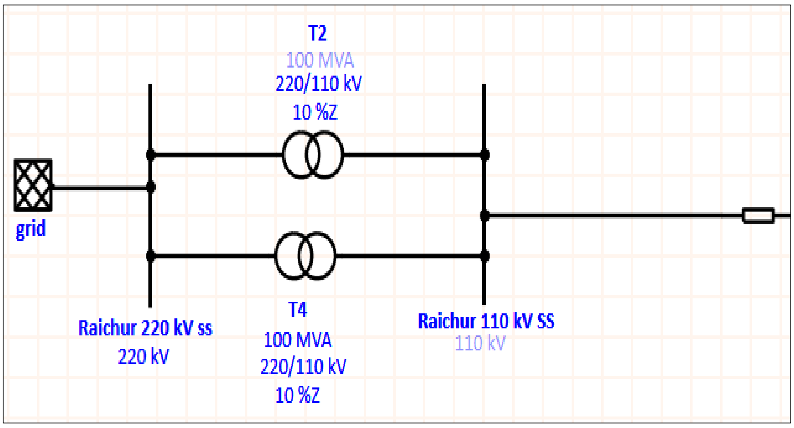

Figure 2. Incoming Supply to the Steel Plant

A power-generating grid (U1) is shown in Figure 2. The Raichur 220 kV substation receives the generated power and uses two transformers (T1 and T3) working in parallel to reduce the voltage from 220 kV to 110 kV [6].

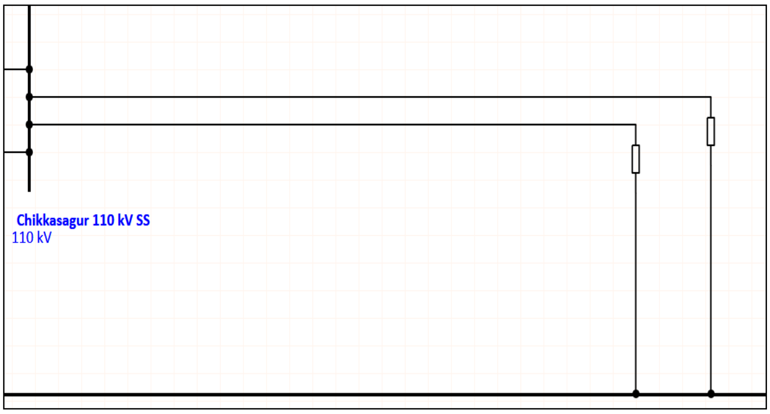

Figure 3. Double Overhead Lines from Chikkasagur Substation to 110 Kv Bus

A lumped load called "Lump1" with a power rating of 10.791 MVA and connected by a transformer is shown in Figure 3. The transformer, known as "Chikkasagur," has a rated capacity of 12.5 MVA and lowers the voltage from 110 kV to 11 kV. The system splits into two main outgoing feeders on the transformer's low-voltage (11 kV) side, which are guarded by circuit breakers with the numbers CB18 and CB19. These feeders continue downstream through additional circuit breakers, CB6 and CB7, which probably lead to different load centers or distribution sections [7].

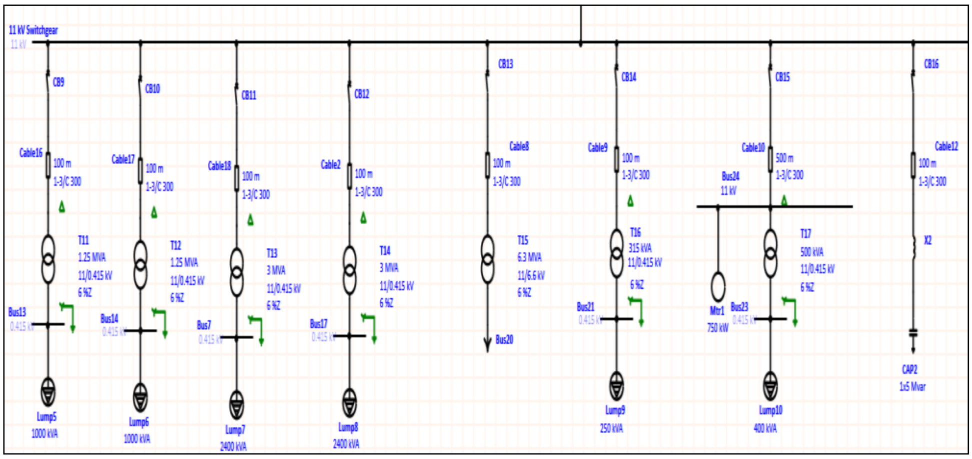

Figure 4. Overview of a Low Voltage Load, Service Loads and Auxiliary Loads

A thorough layout with numerous transformers, cables, buses, loads, and capacitor banks is shown in Figure 4. An 11 kV switchgear connects Lump11 (a 4.8 MVA load) to the left [8]. Power is supplied to multiple buses, including Buses 34, 43, and 45, via a variety of cables and transformers, including T27, T25, T26, T28, and others. To supply various loads, such as Lump15 (1000 kVA), Lump18 (1000 kVA), Lump19 (2400 kVA), Lump21 (2400 kVA), and Lump22 (250 kVA), each transformer reduces voltage. To improve reactive power management and preserve voltage stability, Lump23 (400 kVA) and Lump24 (4.375 MVA) are connected in the right section and are supported by a capacitor bank (CAP3, rated at 145 kvar) [9].

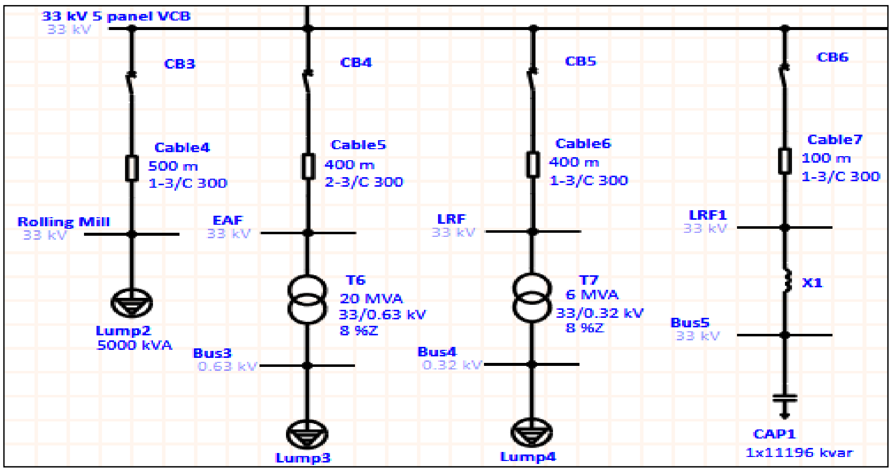

Figure 5. Overview of a Non-Linear Load

A typical 11 kV/0.415 kV commercial or industrial power distribution system is shown in Figure 5. A number of circuit breakers (CB31 to CB34) and 300 mm² rated aluminum cables (Cable29, Cable30, Cable31, and Cable33) carry power from the source to several transformers and loads. Three transformers that each step-down voltage for different loads make up the system: T29 (6.3 MVA, 11/6.6 kV), T30 (315 kVA, 11/0.415 kV), and T31 (500 kVA, 11/0.415 kV). These components are connected by busbars (Bus43, Bus45, Bus47, and Bus48), with Bus43 and Bus47 running at 11 kV and Bus45 and Bus48 at 0.415 kV. A massive 750 kW motor (Mtr1) is directly connected at 11 kV, while lumped loads Lump22 (250 kVA) and Lump23 (400 kVA) are connected at the 415 V level. In order to improve the power factor and compensate for reactive power, a 5 MVAR capacitor bank (CAP3) is also installed at Bus X3 [9].

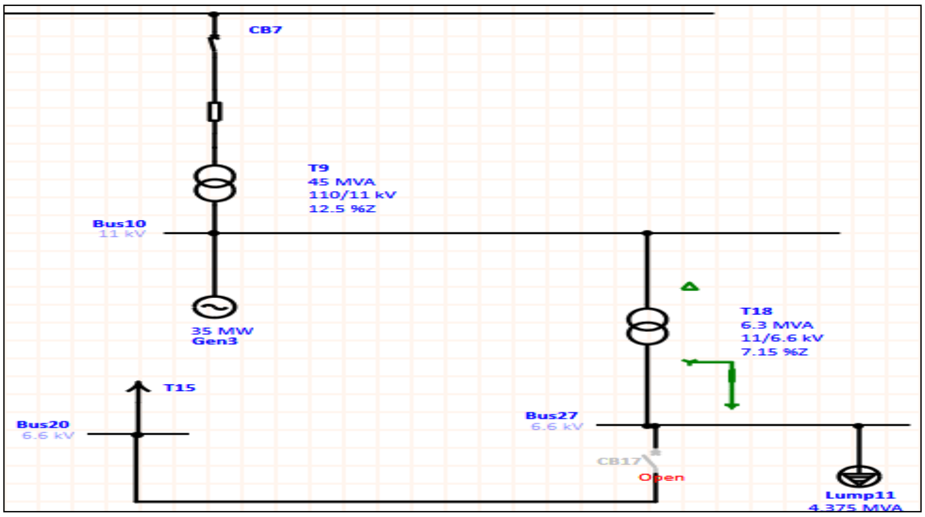

Figure 6. Detailed View of a Cogeneration Plant

A portion of a power distribution network that includes generation, transformation, and load distribution is shown in Figure 6. Bus10 has an 11 kV connection to a 35 MW generator. The transformer T9, which has a 45 MVA capacity and a 12.5% impedance, receives power from Bus10 via Circuit Breaker CB7 and regulates voltage levels between 110 kV and 11 kV. Another transformer, T18, which steps down the voltage from 11 kV to 6.6 kV, is connected to Bus27 further down the network. T18 has an impedance of 7.15%, a secondary rating of 7.15 MVA, and a 6.3 MVA rating. Lump11, the load, has a 4.175 MVA rating and is connected at 6.6 kV. Furthermore, Bus20 is present at 6.6 kV, suggesting the possibility of additional distribution channels or system connections.

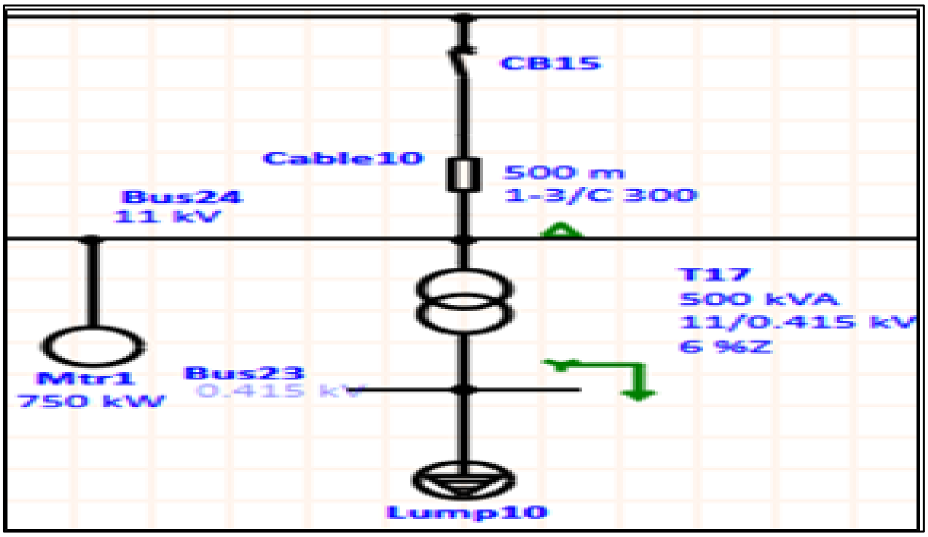

Figure 7. Detailed View of a Motor

Figure 7 shows a motor (Mtr1) with a 750 kW rating that is powered by an 11 kV source (Bus47). A 500-meter-long, 1-core, 300 mm² aluminum (AL) subterranean cable (Cable31) and a circuit breaker (CB33) carry the power. This cable is connected to a 500 kVA transformer (T31) with an impedance of 6% and a voltage ratio of 11 kV/0.415 kV. Bus48 connects to a 400 kVA lumped load (Lump23).

First, a thorough electrical model of the steel sector will be created. Maximum Grid Voltage & Maximum Load, Maximum Grid Voltage & Minimum Load, Maximum Grid Voltage & Average Load, Grid Supply Alone & Maximum Load, and Captive Power Plant (CPP) Supply Alone & Minimum Load are the five operating conditions under which a thorough load flow analysis will be carried out after the modeling phase. To determine whether power generation and demand are suitably balanced under various operating conditions, the outcomes of each scenario will be examined. Conclusions about the system's ability to consistently meet load requirements under various grid and load scenarios will be made in light of the findings.

A medium-voltage power distribution system is shown in Figure 8. In order to provide protection and operational control, the system is interfaced with a grid power source via circuit breakers or isolators. A main horizontal busbar serves as the conduit for electrical power, from which several feeders branch out to supply power to different downstream sections. Repeated breaker and contactor symbols in the diagram's left section indicate multiple parallel feeders that may supply individual loads or local distribution boards, like Motor Control Centers

(MCCs). The diagram's central and right sections show additional distribution to big loads, motors, or step-down transformers, each of which has the necessary switching and protection components. A variety of low-voltage loads, such as motors, lighting systems, and auxiliary equipment, are connected in the lower section; many of these devices have automation controls or switchgear [10].

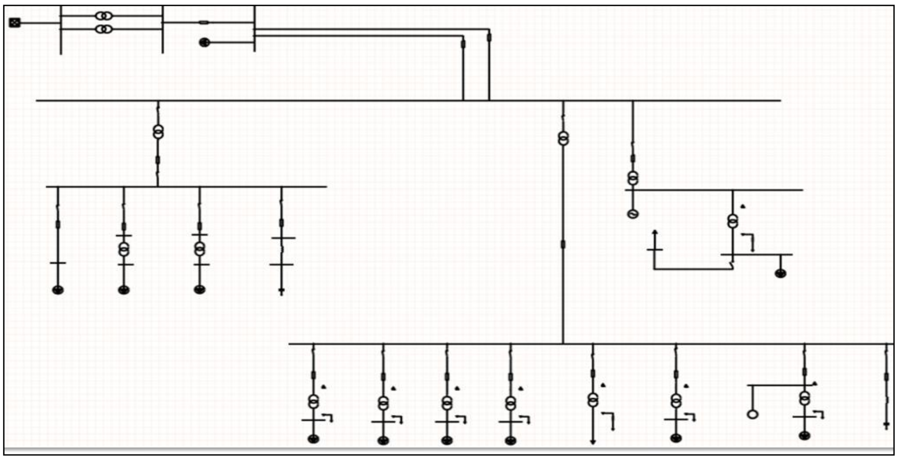

Figure 8. Over View of a Steel Industry

5. Results and Discussion

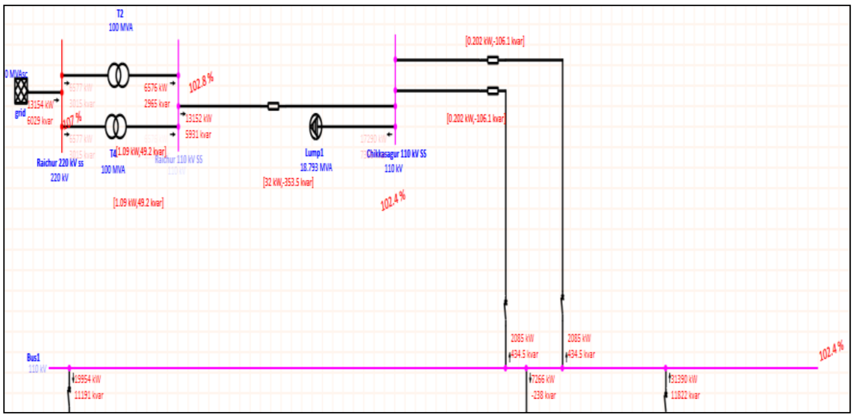

Figure 9. Detailed View of Load Flow Analysis for the Incoming Power Supply to the Steel Industry

The power transfer from the main grid to the 110 kV system is shown in Figure 9 after passing through the Raichur 220 kV substation and being stepped down by two parallel 100 MVA transformers (T1 and T3). At the Raichur 220 kV bus, the incoming active and reactive power is roughly 14.979 MW and -7.173 Mvar, respectively. The load is being shared equally by transformers T1 and T3, which are each sending roughly 7.488 MW and -3.653 Mvar to the Raichur 110 kV substation. The system then distributes power to a lumped industrial load (18.793 MVA) and the Chikkasagar 110 kV substation. With a considerable active (17.290 MW) and reactive (7.366 Mvar) power demand at the Chikkasagar substation, the real and reactive power flow at different buses suggests a heavy load condition. There are slight transformer losses (shown by 1.48 MW and 66.4 kVar losses in T3) [11].

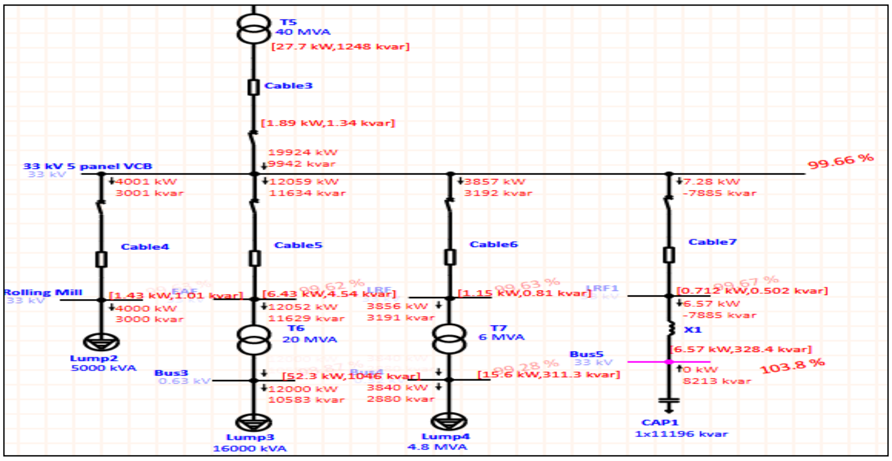

Figure 10. Detailed View of Load Flow Analysis for Non-Linear Loads Under Normal Conditions

The power distribution from the 110 kV bus via a 40 MVA transformer (T7) that steps down to the 33 kV system is shown in Figure 10. Significant industrial loads, such as an Electric Arc Furnace (EAF), a Ladle Refining Furnace (LRF), and multiple lumped loads, are supplied by the 33 kV side. Operating at roughly 99.36% to 99.39% of their rated capacity, the cables—including Cable5, Cable8, and Cable15—serving these loads are heavily loaded. Furthermore, for reactive power compensation, Buses 15 and 16 are linked to capacitor banks (CAP1-11.196 Mvar). Bus16, which runs at 105.6%, is clearly overloaded, suggesting possible hazards under continuous operation.

A 35 MW captive generator (Gen2) is modeled on the system's right side, but it provides very little active power, indicating that the system is mostly dependent on grid power. Additionally connected for captive generation and distribution are transformers T21 (15 MVA) and T20 (45 MVA). Significant 5th- and 7th-order harmonics are introduced into the system at Surana Steel by large non-linear loads, such as a 35 MW electric arc furnace and a ladle refining furnace. The plant uses an 11.196 Mvar tuned passive filter on the 33 kV bus to keep the voltage waveform clean.

In ETAP, this filter was recreated with the precise tuning frequency, Q-factor, and kvar rating provided by the manufacturer. When the furnaces operated at full capacity, the software predicted that total harmonic distortion (THD) on the 33 kV bus would decrease from 6.2% to 4.8% upon activation of the filter. Measurements taken on-site using a power quality analyzer corroborated this trend, with THD reducing from 6.1% to 4.6%. The simulated and measured values never deviated by more than approximately 0.2%, demonstrating that ETAP can accurately replicate the filter's real-world performance, provided that the model is configured with precise and reliable filter specifications.

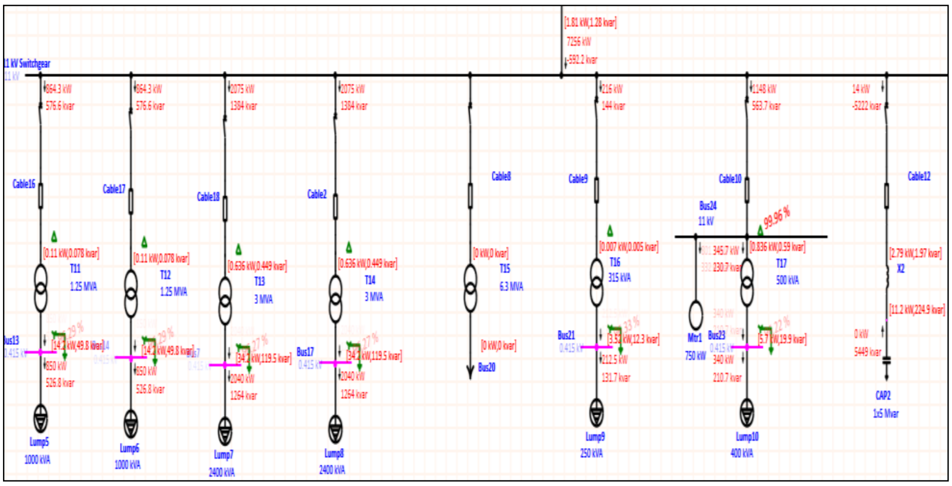

Figure 11. Detailed View of Load Flow Analysis for Low Voltage and Auxiliary Loads Under Normal Conditions

An 11 kV switchgear powers the system in Figure 11, and it branches out into several feeders using transformers and cables, such as Cables 22, 25, 26, and 28. Several transformers (T72, T75, T76, and T78) as well as sizable motors and industrial machinery (represented by Lump15, Lump18, Lump19, and Lump21) make up the connected lumped loads. Notably, there is a considerable reactive power demand in some sections, especially at Cable33 and CAP3 (1.5 Mvar capacitor bank), and some components, like Cable31 and the related buses, are slightly overloaded (100.4%).

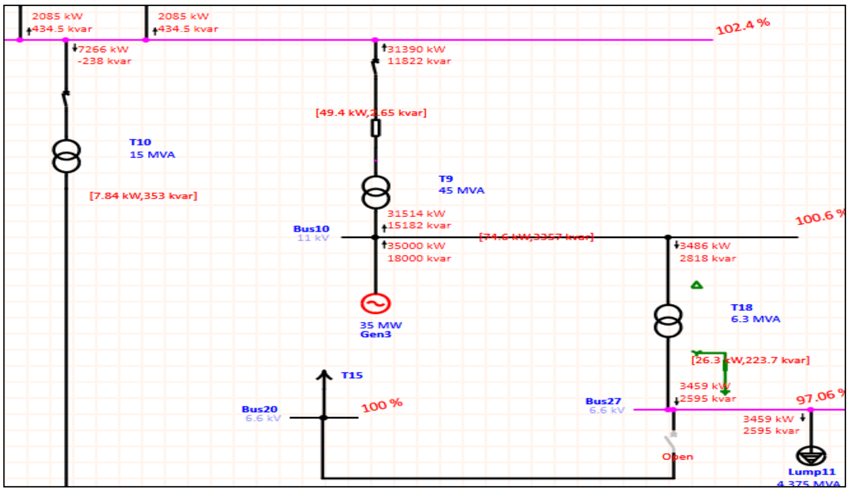

Figure 12. Detailed View of Load Flow Analysis for a Co-Generation Plant Under Normal Conditions

Figure 12 represents Detailed View of Load Flow Analysis of a Co-Generation Plant Under Normal Condition, the main incoming lines and cables are heavily overloaded, with loading percentages reaching 115.2%, 118.3%, and 116.2%. Key transformers like T20 and T21 are linked, and the network is also receiving power from the 35 MW Gen2 generator. The system's overall power factor is low due to significant reactive power flows (high kvar values). It appears that the reactive power compensation is inadequate because Cable 10 and the connected capacitor bank (CAP1, 11.196 Mvar) are overloaded. The network is under additional stress due to connected loads like Lump24, and Bus3 (6.6 kV) and Bus5 are marginally overloaded at 102–103%. Overall, there is active and reactive power congestion in the network. To prevent equipment damage and preserve voltage stability, quick fixes like load redistribution, additional capacitor banks, transformer upgrades, or feeder splitting are required. The 35 MW turbine generator at Surana Steel is an essential component of the power system, particularly during captive mode operations. Important parameters like the generator's inertia constant, governor response, and exciter characteristics were entered using actual data gathered from the site in order to evaluate how accurately ETAP modeled the dynamic behavior of the generator. To simulate the abrupt spike in demand brought on by the electric arc furnace's startup, a load disturbance scenario was created in ETAP. The system frequency briefly dropped, but it recovered to 50 Hz in about 4.2 seconds, according to the results. This closely matched field measurements, which showed that it took around 4.0 seconds for the generator frequency to return to normal. The slight variation demonstrates how ETAP, when set up with precise operational data, can accurately model the dynamic response of on-site generators.

CONFIGURATION	VOLTAGE	LOAD
Normal	Maximum	Maximum
Normal	Maximum	Minimum
Normal	Maximum	Average
CPP	Maximum	Minimum
Grid Alone	Maximum	Maximum

Figure 13. Different Case Scenario

Different operating conditions for load flow analysis in the power system of a steel facility are shown in Figure 13. It offers five different setups for assessing system performance. The Normal configuration is represented by the first three scenarios, in which the load fluctuates between maximum, minimum, and average values, respectively, while the voltage is continuously maintained at its maximum level. These hypothetical situations make it easier to evaluate how the system would behave in both normal and variable demand situations. In the fourth scenario, the system functions autonomously at maximum voltage but with minimal load thanks to the Captive Power Plant (CPP) configuration. In this scenario, the facility's own generation powers operations with low or partial demand. The fifth scenario, Grid Alone, depicts a situation where the facility runs at maximum voltage and maximum load and is totally dependent on the external grid. This configuration is essential for independently assessing the grid's ability to support all industrial demand. In order to ensure voltage stability, power quality, and system reliability under a variety of operating conditions, these case scenarios taken together are essential for a thorough load flow study.

	Study ID	CPP Min Load	Gr Max V Min L	Max V Max L	Max V Min L	Untitled
1	Study Case ID	Max V Min L	Max V Max L	Max V Max L	Max V Min L	Max V Min L
2						
3	Data Revision	Base	Base	Base	Base	Base
4	Configuration	CPP Alone	Grid Alone	Normal	Normal	Normal
5						
6	Loading Cat	Min Load	Max Load	Max Load	Min Load	Min Load
7	Generation Cat	Max V	Max V	Max V	Max V	Max V
8	Diversity Factor	Global MF	Global MF	Global MF	Global MF	Global MF
9						
10	Buses	31	31	34	34	34
11	Branches	30	32	35	35	35
12	Generators	1	0	1	1	1
13	Power Grids	0	1	1	1	1
14	Loads	11	11	12	12	12
15						
16	Load-MW	8.902	44.264	47.724	14.086	14.086
17	Load-Mvar	-9.848	14.477	17.006	-4.754	-4.754
18	Generation-MW	8.967	44.919	48.154	14.422	14.422
19	Generation-Mvar	-8.617	19.594	23.847	0.117	0.117
20	Loss-MW	0.0645	0.655	0.431	0.336	0.336
21	Loss-Mvar	1.232	5.116	6.841	4.87	4.87
22						
23	Mismatch-MW	0	0	0	0	0

Figure 14. Load Flow Analyser of the Case Scenario

The system's performance under various operational scenarios, including varying load and voltage conditions, is depicted in Figure 14. The system reaches its peak demand with an active power flow of 47.724 MW and reactive power of 17.006 Mvar under maximum grid voltage and maximum load. On the other hand, the active power drops to 14.086 MW and the reactive power turns negative at -4.754 Mvar when the load is decreased while keeping the grid voltage at its maximum. This suggests that the steel plant is absorbing reactive power. Significantly, as shown in Figure 15, the maximum voltage and average load scenario displays the same values as the minimum load case, possibly as a result of data overlap or comparable operational behavior. As seen graphically in Figure 17, the grid provides 44.264 MW of active power and 14.477 Mvar of reactive power in the grid-alone configuration under maximum load conditions. This is marginally less than the maximum seen in the entire system. Last but not least, as shown in Figure 16 [12], the captive power plant absorbs a substantial reactive power of -9.848 Mvar while managing a modest active load of 8.902 MW in the CPP-alone scenario with minimum load.

ETAP software was used to perform the load flow analysis, which assessed the power system's performance under a range of operating conditions, such as minimum load conditions, grid maximum voltage with minimum load, CPP minimum load, and maximum voltage with maximum load. The findings show that under all conditions, the system stays stable and functions within reasonable bounds. Zero-megawatt mismatch values demonstrate that power generation continuously and consistently satisfies load demand. The robustness of the system design was highlighted by the fact that the diversity factors, buses, and branches were all set up appropriately to support the load. The power system's ability to function dependably under both minimum and maximum load conditions while preserving voltage stability, effective power flow, and low losses is generally confirmed by the load flow study. In order to ensure efficient power system planning and well-informed operational decision-making, this analysis is an essential step [13].

5.1 Accuracy Assessment of Reactive Power Flow in ETAP

By contrasting simulation results with real-time measurements from important buses and feeders, the accuracy of ETAP's reactive power flow predictions was assessed as part of the power flow analysis for the Surana Steel facility. Particularly under the "maximum grid voltage and maximum load" scenario, the evaluation focused on the high-voltage distribution network under full-load conditions. ETAP's reactive power (MVAr) values were contrasted with handheld power analyzer readings and logged SCADA data at multiple sites, including the 33 kV and 11 kV buses. When compared to field measurements, ETAP consistently predicted reactive power flow within a ±6% deviation range in every case. The electric arc furnace's feeder experienced the biggest deviation, which was probably caused by its rapidly changing load and varying power factor. However, the simulation accurately depicted the overall trend and magnitude of reactive power. This degree of accuracy attests to ETAP's ability to accurately estimate reactive power behavior in intricate industrial systems, provided the model is created using exact load profiles and network configurations.

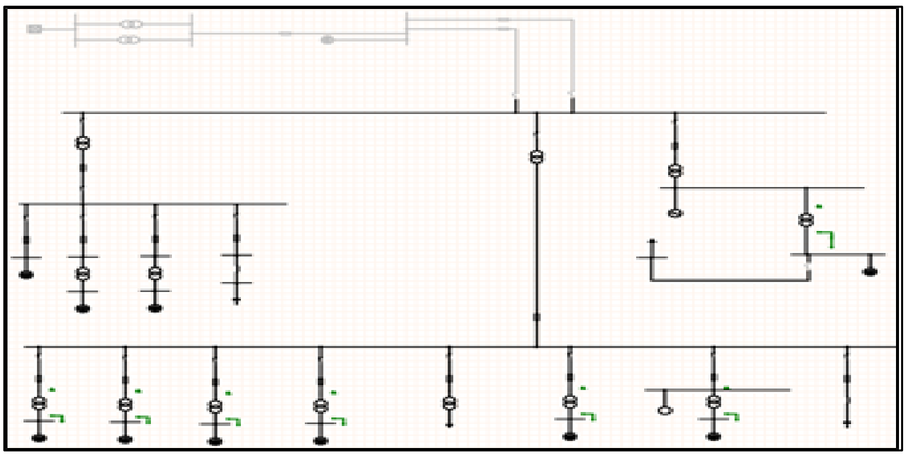

Figure 15. Overview of Load Flow Analysis During Normal Operation

The steel industry's electrical network under normal operating conditions is shown in Figure 15, where load-sharing and increased reliability are achieved by synchronous power supply from the utility grid and the captive power plant (co-generation unit).

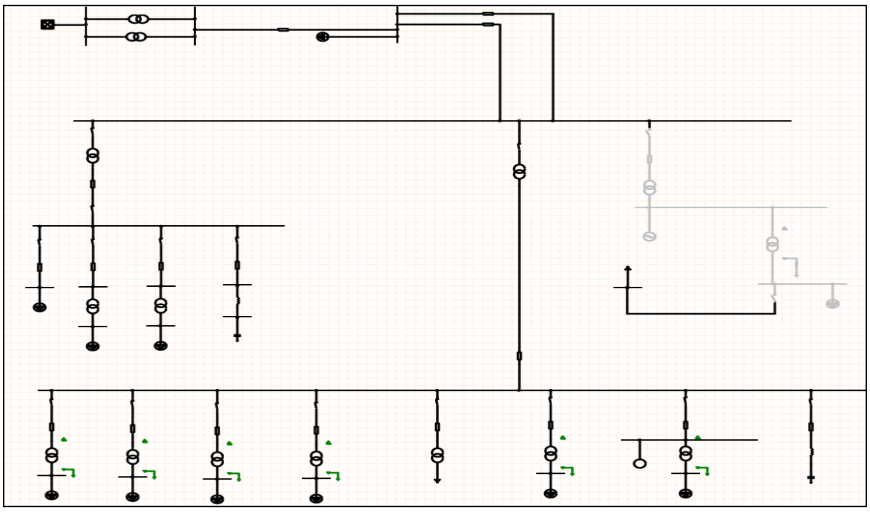

Figure 16. Overview of Grid Alone Power Supplies to the Steel Industry

The grid-alone configuration, shown in Figure 16, disconnects the co-generation unit and feeds the steel plant exclusively from the external utility grid. Usually, this mode is employed when there is little plant load.

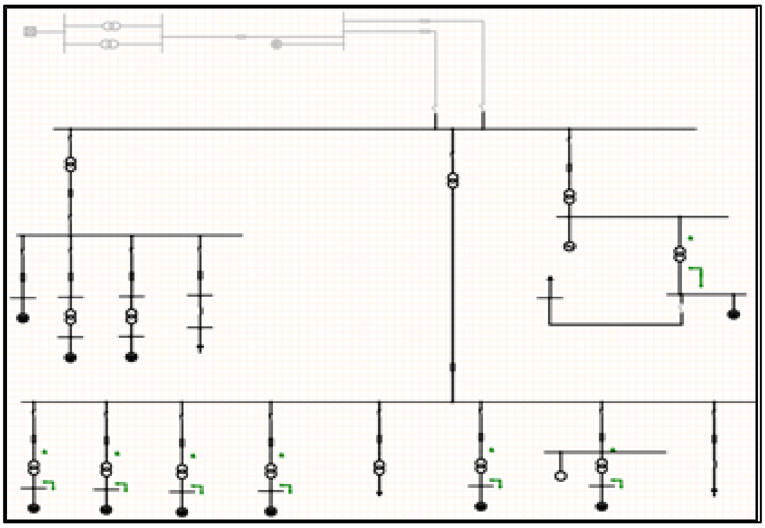

Figure 17. Overview of Co-Generation Plant Alone Power Supplies to the Steel Industry

The co-generation-only mode, shown in Figure 17, is when the captive power plant solely provides for the steel industry's electrical needs. This setup is crucial for grid outages and for islanded operation, which optimizes energy costs.

5.2 Transformer Tap-Changer Performance Verification in Industrial Load Scenarios

A thorough comparison between simulation results and real-world field data from the Surana Steel Industry was conducted in order to evaluate the accuracy of ETAP's transformer modeling, specifically its approach to impedance and automatic tap-changing behavior. Using manufacturer-provided parameters, ETAP was used to model the facility's two main grid-connected transformers, each rated at 100 MVA (220/110 kV) with 10% impedance. The on-site On Load Tap Changer (OLTC) configuration was reflected in the tap-changer settings, which were set with a ±10% range in 1.25% increments. ETAP anticipated a tap-down operation on transformers T1 and T3 to preserve voltage stability at the 110 kV bus during times of high load, particularly under maximum grid voltage and peak demand conditions (47.724 MW and 17.006 MVAr). Similar voltage dips, mostly caused by furnace operations, were successfully addressed by two tap adjustments, according to plant SCADA logs. This closely matched ETAP's simulated response of about ±1.3% from nominal voltage. The difference between the measured and simulated secondary voltages was within ±1.5% for each of the five operational scenarios that were studied. This robust correlation confirms that ETAP faithfully captures the behavior of actual transformers, including both dynamic OLTC responses and impedance-induced voltage drops. The results validate ETAP's ability to model intricate industrial power systems with high, fast-changing loads, which are common in steel mills.

5.3 Assessment of ETAP's Performance Under Unbalanced Load Conditions

Significant phase-to-phase load imbalances can arise in the steel plant environment, especially during the on/off switching of large single-phase equipment like auxiliary motors and induction furnaces. The model was set up with exact cable impedances, transformer vector groups, and per-phase load distributions measured on-site on a day with high imbalance in order to evaluate ETAP's ability to analyze unbalanced load flow. The maximum Voltage Unbalance Factor (VUF) at the 11 kV feeder supplying the induction motors was estimated by ETAP's Unbalanced Load Flow solver to be 1.9%. Under the same operating conditions, field measurements using a three-phase power analyzer showed a peak VUF of 2.0%. Per-phase current predictions were within 5% of actual values, and the average difference between simulated and measured VUF for all feeders under observation stayed below 0.2%. These findings show that ETAP can accurately represent both voltage and current imbalances in intricate industrial systems when it is set up with precise phase-wise load data and actual network parameters.

5.4 Scope of the Power Flow Analysis for the Steel Industry

In ETAP, a comprehensive digital model of the power network of Surana Steel Industry was created, including all transformers, the on-site generator, significant lumped and motor loads, and installed reactive power equipment. Five different operating conditions were used to evaluate the model: (1) maximum-voltage grid supply at peak load, (2) maximum-voltage grid supply at light load, (3) maximum-voltage grid supply at typical (average) load, (4) grid-only operation at peak load, and (5) CPP-only operation at light load. The flow of active and reactive power through the buses, transformers, and feeder lines was investigated, and bus voltage levels were carefully examined in each operating scenario to find any deviations from their nominal values. Several transformers and cables were found to be operating close to or above their thermal capacity, especially in situations involving high demand and cogeneration, according to the analysis. Furthermore, notable deficiencies in reactive power were noted, which the current capacitor banks were unable to adequately address. All scenarios' power losses and overall system efficiency were evaluated, emphasizing the different load contributions from captive generation and grid supply. In order to alleviate overloaded components, improve voltage stability, and fortify the system's preparedness for future expansion, the study suggests rearranging portions of the network, improving reactive power compensation, and putting load redistribution strategies into practice.

5.5 Strengths and Limitations of the Methodology

Power flow analysis using ETAP, the methodology used in this study, has a number of unique advantages that are pertinent to the assessment of industrial power systems. Large-scale systems, like those in the steel industry, can be meticulously modeled thanks to ETAP's sophisticated simulation capabilities and graphical user interface. Analyzing voltage profiles, transformer loading, reactive power compensation, and system losses in detail is made easier by the ability to model various operating scenarios, such as different load levels and power supply configurations. Reliable results for steady-state operational analysis are guaranteed by the software's accuracy in solving nonlinear algebraic equations.

But there are drawbacks to this strategy. First, dynamic events like transients, the effects of load switching, or fault-induced instabilities are not included in the analysis, which is limited to steady-state conditions. Furthermore, although ETAP has modules for transient, harmonic, and short circuit analysis, these were not investigated in this study, leaving gaps in areas like fault coordination and power quality evaluation. The findings are also predicated on idealized assumptions that may not accurately reflect real-world circumstances, such as shifting industrial demands and system aging, such as constant load profiles and flawless component behavior.

In conclusion, even though the methodology offers a solid basis for assessing steady-state performance and organizing operational enhancements, additional incorporation of dynamic, harmonic, and protection studies would strengthen the analysis's completeness and robustness, especially in intricate industrial settings like steel plants.

6. Future Scope

The power flow analysis of steel industry power systems provides a solid foundation for enhancing operational efficiency and system reliability. However, to further strengthen the power system's robustness, future studies should focus on detailed short circuit analysis to assess fault levels and protective device requirements more accurately [14]. This will enable the design and implementation of effective relay coordination schemes, ensuring timely fault detection and isolation, minimizing equipment damage, and enhancing personnel safety. Additionally, considering the increasing integration of nonlinear loads and power electronic devices in steel plants, harmonic analysis is critical to identify and mitigate power quality issues that can adversely affect sensitive equipment and reduce system efficiency. Furthermore, incorporating renewable energy sources and energy storage systems into the steel industry's power network presents opportunities for more sustainable and cost-effective operation.

7. Conclusion

A strong basis for improving operational effectiveness and system dependability is established by the power flow analysis of power systems in the steel sector. Future studies should focus on thorough short circuit analysis to more precisely determine fault levels and the need for protective devices in order to further increase the power system's resilience. This strategy will make it easier to create and execute efficient relay coordination plans, guaranteeing prompt fault identification and isolation, reducing equipment damage and improving worker safety. Harmonic analysis is also crucial for detecting and resolving power quality problems that could negatively impact delicate equipment and reduce system efficiency, especially as nonlinear loads and power electronic devices are increasingly integrated in steel plants. Furthermore, opportunities for more economical and sustainable operations are presented by the integration of energy storage devices and renewable energy sources into the steel industry's power network.

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