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Analysis of Motor Acceleration Performance and Harmonics for a Data Center

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Abstract: Data centers are highly sensitive electrical infrastructures that require reliable power supply, voltage stability, and high-power quality due to the presence of critical IT loads, HVAC systems, Uninterruptible Power Supplies (UPS), and Variable Frequency Drives (VFDs). The increasing penetration of non-linear loads introduces harmonic distortions, while large motor starting operations can cause significant voltage dips and affect system stability. This paper presents the modeling and analysis of a 13.8 kV/0.4 kV data center electrical network using ETAP software. The system includes medium-voltage ring main units (RMUs), distribution transformers, low-voltage networks, and critical/non-critical loads. Motor acceleration studies were performed to evaluate starting current, acceleration time, voltage drop, and motor terminal performance for major induction motors under starting conditions. In addition, harmonic analysis was carried out to assess voltage and current distortion levels caused by VFD-driven HVAC motors and UPS systems, with compliance verification based on IEEE 519 standards. The study results demonstrate the impact of motor starting on bus voltage profiles and identify harmonic levels across different buses in the system. The analysis confirms system operational reliability under normal conditions and provides recommendations for improving power quality and ensuring stable operation of data center electrical infrastructure.

Keywords: Load Flow Analysis, Harmonics Analysis, Motor Acceleration, ETAP, Industrial Power Systems, IEC 60909, IEEE 519.

I. INTRODUCTION

The rapid growth of cloud computing, digital storage, artificial intelligence applications, and internet-based services has significantly increased the demand for reliable and efficient data center infrastructure. Data centers are critical facilities that require continuous, uninterrupted, and high-quality power supply to support sensitive Information Technology (IT) equipment, cooling systems, and auxiliary electrical loads. Even minor disturbances in power quality can result in equipment malfunction, system downtime, financial losses, and reduced operational reliability.

Modern data centers employ a large number of power electronic devices such as Uninterruptible Power Supply (UPS) systems, Variable Frequency Drives (VFDs), switched-mode power supplies, and large induction motors for HVAC and cooling applications. Although these devices improve operational efficiency and system controllability, they introduce several power quality challenges including harmonic distortion, voltage fluctuations, and transient disturbances. Additionally, the starting of large induction motors can draw high inrush currents, causing voltage dips that may adversely affect other connected loads within the electrical distribution network.

Therefore, detailed power system studies are essential to ensure the reliable and safe operation of data center electrical infrastructure. Among various studies, motor acceleration analysis and harmonic analysis play a crucial role in evaluating system performance under dynamic and non-linear operating conditions. Motor acceleration analysis is used to assess motor starting characteristics such as starting current, acceleration time, torque-speed behavior, and bus voltage variation during starting conditions. This helps verify whether motors can successfully accelerate to rated speed without causing unacceptable voltage drops or instability in the system.

Similarly, harmonic analysis is performed to evaluate the impact of non-linear loads on voltage and current waveform distortion. Excessive harmonics can lead to transformer overheating, increased losses, malfunction of protection devices, reduced equipment lifespan, and poor power factor. Compliance with standards such as IEEE 519 is necessary to maintain acceptable harmonic limits and ensure power quality in critical facilities.

In this study, the electrical network of the EDGNEX Data Center located in Riyadh, Saudi Arabia, is modeled using ETAP software. The system consists of a 13.8 kV medium-voltage ring main network, multiple distribution transformers, low-voltage distribution systems, UPS-integrated IT loads, and HVAC motors driven by VFDs. Motor acceleration and harmonic studies are conducted to evaluate the performance of the electrical system under motor starting and harmonic loading conditions. The results provide valuable insights into voltage stability, harmonic distortion levels, and overall operational reliability of the data center power system.

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II. EGDNEX DATA CENTER ELECTRICAL DISTRIBUTION SYSTEM

The EDGNEX Data Center is designed with a highly reliable electrical infrastructure to ensure uninterrupted power supply for critical IT and mechanical loads, including cooling and HVAC systems. The facility is supplied from a 13.8 kV medium-voltage utility grid and incorporates redundancy to maintain continuous operation, as power interruptions in data centres can lead to operational and financial losses.

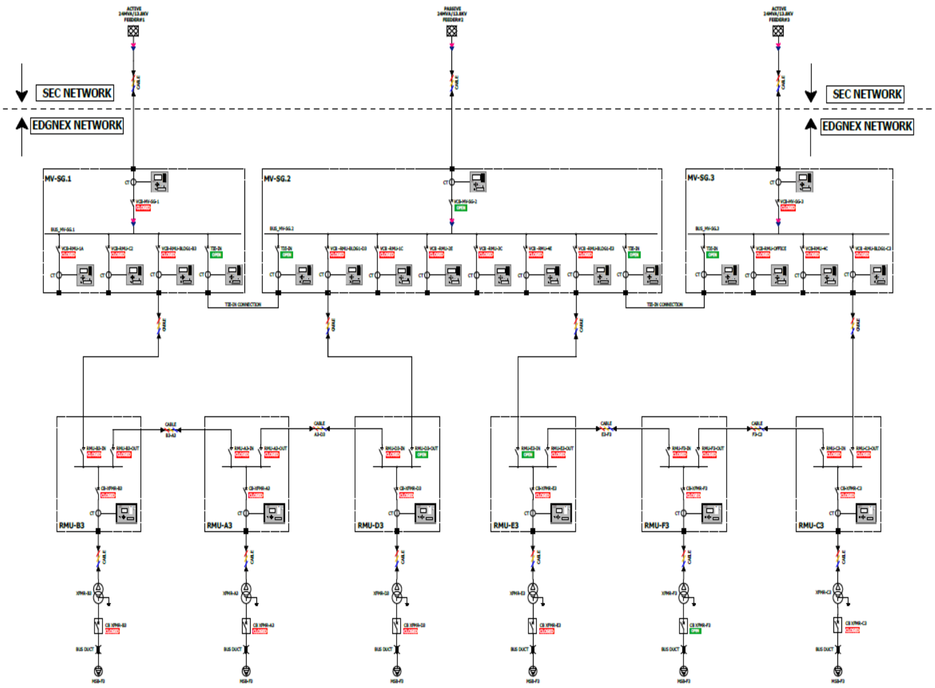

Figure 1 Medium Voltage Single Line Diagram (MV SLD) of EDGNEX Data Center.

Figure 1 illustrates the Medium Voltage Single Line Diagram (MV SLD) of the EDGNEX Data Center, showing the power distribution from the utility source to downstream loads. The system follows a loop-based architecture interfaced with both the SEC and EDGNEX networks, enabling alternate power paths during faults or maintenance conditions, thereby improving operational reliability and minimizing downtime.

III. METHODOLOGY

The methodology adopted in this study involves a systematic simulation-based analysis of the electrical distribution network of the EDGNEX Data Center using ETAP software. The study focuses on evaluating the system performance under both steady-state and dynamic operating conditions, with particular emphasis on motor acceleration characteristics and harmonic distortion analysis.

A. System Modeling In ETAP

A detailed electrical model of the EDGNEX Data Center was developed in ETAP based on the actual single-line diagram and design specifications of the facility. The model includes utility sources, medium voltage switchgear, Ring Main Units (RMUs), transformers, low-voltage distribution panels, Uninterruptible Power Supply (UPS) systems, Variable Frequency Drives (VFDs), and critical motor loads associated with HVAC and cooling infrastructure.

The medium voltage distribution system figure 2 operates at 13.8 kV and is configured with a loop-based architecture to ensure redundancy and uninterrupted power supply. The network model was created by incorporating equipment ratings, cable parameters, transformer impedances, source short-circuit capacities, and load characteristics. This detailed modeling approach ensures accurate representation of practical operating conditions within the data center electrical infrastructure.

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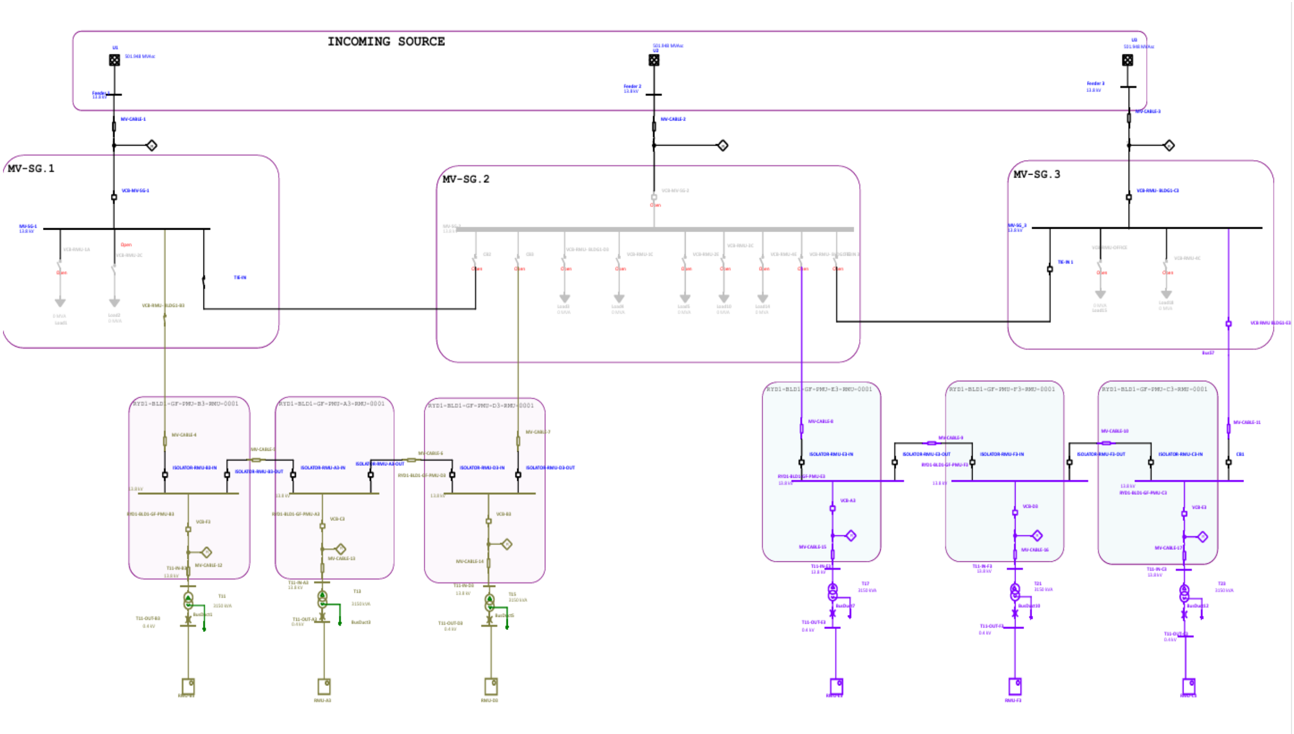

Figure 2 MV network of EGDNEX DATA center

B. Load flow analysis

Prior to performing dynamic studies, load flow analysis was conducted to establish the steady-state operating condition of the electrical network. The Adaptive Newton–Raphson method available in ETAP was used to determine bus voltage magnitudes, voltage angles, active power flow, reactive power flow, transformer loading, and system losses.

The load flow study serves as the foundation for all subsequent analyses by validating that the electrical network operates within acceptable voltage and loading limits under normal operating conditions. The results obtained from load flow analysis also provide the initial operating conditions required for motor acceleration simulation.

C. Motor acceleration Analysis

Motor acceleration analysis was carried out to evaluate the dynamic behavior of large induction motors during startup conditions. In data center environments, large motors used for chillers, pumps, and HVAC systems draw significant inrush current during starting, which may result in temporary voltage dips across the electrical network.

A time-domain simulation approach was adopted in ETAP to analyze the starting performance of selected motors. The induction motor model includes both electrical and mechanical parameters such as stator resistance, rotor resistance, leakage reactance, inertia constant, and load torque characteristics.

During simulation, the motor starting event was initiated under predefined operating conditions, and key system parameters were monitored throughout the acceleration period. The following performance indicators were evaluated:

- Bus voltage profile during motor startup
- Motor terminal voltage
- Starting current magnitude
- Acceleration time
- Rotor speed response
- Electromagnetic torque characteristics
- Reactive power demand during startup

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The analysis was continued until the motor reached rated speed and all dynamic variables stabilized. The obtained results were compared against IEEE recommended voltage dip criteria to ensure that motor starting does not adversely affect sensitive IT equipment or UPS systems.

D. Harmonics Analysis

Harmonic analysis was performed to assess the impact of nonlinear loads on power quality within the data center electrical network. Major harmonic-producing loads considered in this study include UPS systems, Variable Frequency Drives (VFDs), switch mode power supplies (SMPS), and rectifier-based electronic equipment.

A frequency-domain harmonic simulation was carried out in ETAP by modeling nonlinear loads as harmonic current injection sources with predefined harmonic spectra. Harmonic orders up to the 50th order were analyzed to capture both lower-order and higher-order distortion effects.

The following harmonic performance parameters were evaluated:

• Voltage Total Harmonic Distortion (THDv)
• Current Total Harmonic Distortion (THDi)
• Individual Harmonic Distortion (IHD)
• Harmonic voltage profile at critical buses

The calculated distortion levels were compared with IEEE 519-2022 recommended limits to verify compliance with accepted power quality standards.

E. PERFORMANCE EVALUATION AND VALIDATION

The final stage of the methodology involved evaluating the simulation results obtained from both motor acceleration and harmonic studies. The electrical network performance was validated based on:

• Voltage stability during motor starting
• Successful motor acceleration without prolonged startup duration
• Compliance with harmonic distortion limits
• Overall system reliability and operational stability

This integrated methodology provides a comprehensive framework for analyzing the electrical performance of data center distribution systems and validating their capability to support critical loads under practical operating conditions.

IV. RESULT AND DISCUSSION

The simulation studies were carried out in ETAP to evaluate the electrical performance of the EDGNEX Data Center under both steady-state and dynamic operating conditions. The analysis includes load flow, motor acceleration, and harmonic studies to validate the reliability and power quality performance of the electrical distribution system.

A. Load flow analysis result

Load flow analysis was performed to determine the voltage profile, active and reactive power flow, transformer loading, and system losses under normal operating conditions.

The simulation results indicate that all buses within the electrical network operate within the acceptable voltage tolerance limit of ±5% as recommended by industry standards. The bus voltages remained close to nominal values, demonstrating adequate voltage regulation throughout the distribution system.

Transformer loading analysis confirmed that all transformers operate within their rated capacity without any overload conditions. Similarly, feeder loading and cable current levels were found to be within permissible operating limits, ensuring reliable system operation under steady-state conditions.

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The load flow results validate that the designed electrical infrastructure is capable of supplying the connected loads efficiently while maintaining acceptable voltage stability and power flow distribution.

Table 1 Load Flow Analysis Result

ID	Rating/Limit	Rated kV	MW	Mvar	Amp	% PF
U1	501.948 MVA	13.8	6.248	1.853	272.6	95.87
U2	501.948 MVA	13.8	0	0	0	0
U3	501.948 MVA	13.8	6.197	1.815	270.1	95.97

ID	Rating/Limit	Rated kV	kW	kvar	Amp	% PF	% Loading	Vterminal %
A3-CRAC-0001 DUTY	55.6 kW	0.4	54.12	24.12	88.63	91.34	93.3	96.49
A3-CRAC-0001 DUTY1	55.6 kW	0.4	54.12	24.12	88.8	91.34	93.5	96.3
A3-CRAC-0001 DUTY5	55.6 kW	0.4	54.12	24.12	88.03	91.34	92.6	97.15
A3-CRAC-0002 STANDY BY3	55.6 kW	0.4	54.12	24.12	88.41	91.34	93	96.73
A3-CRAC-0002 STANDY BY4	55.6 kW	0.4	54.12	24.12	88.21	91.34	92.8	96.95
A3-DX-IDU-0001 DUTY	3 kW	0.4	3.29	2.1	5.826	84.37	93	96.73
A3-DX-IDU-0001 DUTY1	3 kW	0.4	3.29	2.1	5.838	84.37	93.2	96.54
A3-DX-IDU-0001 DUTY3	3 kW	0.4	3.29	2.1	5.806	84.37	92.7	97.07
A3-DX-IDU-0001 DUTY4	3 kW	0.4	3.29	2.1	5.793	84.37	92.5	97.29
A3-DX-IDU-0001 DUTY5	3 kW	0.4	3.29	2.1	5.787	84.37	92.4	97.39
C3-CRAC-0001 DUTY	55.6 kW	0.4	54.12	24.12	88.15	91.34	92.8	97.02
C3-DX-IDU-0001 DUTY	3 kW	0.4	3.29	2.1	5.791	84.37	92.5	97.32
CRFW-0001	25.3 kW	0.4	25.4	12.69	42.28	89.46	92.8	96.94
CRFW-2	25.3 kW	0.4	25.4	12.69	42.09	89.46	92.4	97.39
CRFW-0002	25.3 kW	0.4	25.4	12.69	42.28	89.46	92.8	96.94
CRFW-3	25.3 kW	0.4	25.4	12.69	42.09	89.46	92.4	97.39
CRFW-0003	25.3 kW	0.4	25.4	12.69	42.28	89.46	92.8	96.94
CRFW-4	25.3 kW	0.4	25.4	12.69	42.09	89.46	92.4	97.39
CRFW-0004	25.3 kW	0.4	25.4	12.69	42.28	89.46	92.8	96.94
CRFW-9	25.3 kW	0.4	25.4	12.69	42.02	89.46	92.3	97.55

Based on the load flow analysis results, all bus voltages are within the permissible limits (typically 95% to 105% of nominal voltage), and no voltage violations are observed. The loading of transformers, cables, and other equipment is within their rated capacities, indicating that the system is operating safely without any overloading conditions.

B. MOTOR ACCELERATION ANALYSIS RESULTS

Motor acceleration analysis was conducted to assess the dynamic performance of large induction motors connected to HVAC and cooling systems during startup conditions.

The simulation results show that the motor experiences a high inrush current during initial energization, which is characteristic of induction motor starting behaviour. This starting current caused a temporary voltage dip across critical buses within the electrical network.

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However, the voltage drop observed during motor startup remained within acceptable short-duration voltage dip limits. The system demonstrated sufficient short-circuit strength and reactive power support to withstand the transient disturbance without causing operational instability.

The motor successfully accelerated from standstill to rated speed within the allowable acceleration time. Rotor speed increased smoothly without oscillatory behaviour or prolonged startup duration. Electromagnetic torque developed adequately throughout the acceleration period, indicating successful motor starting performance.

Following motor acceleration, the bus voltages recovered rapidly to their steady-state values, confirming stable system recovery after transient disturbance.

These results demonstrate that the electrical distribution network is capable of supporting large motor startup events without adversely affecting sensitive data centre equipment or UPS-supported loads.

Table 6.9: Voltage Profile

Status Time(sec)	Bus	Voltage Rating (kV)	Voltage (kV)	Voltage (%)	Remarks
Before starting (Time=0)	RYD1-BLD1-FF-A3	0.400	0.398	99.40	OK
	RYD1-BLD1-FF-B3	0.400	0.394	98.15	OK
	RYD1-BLD1-FF-D3	0.400	0.396	99.12	OK
	RYD1-BLD1-FF-D3	0.400	0.396	99.89	OK
	RYD1-BLD1-FF-E3	0.400	0.391	97.89	OK
	RYD1-BLD1-FF-F3	0.400	0.393	98.26	OK
Status Time(sec)	Bus	Voltage Rating (kV)	Voltage (kV)	Voltage (%)	Remarks
	RYD1-BLD1-FF-A3	0.400	0.360	90.21	OK
	RYD1-BLD1-FF-B3	0.400	0.357	89.45	OK

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Before starting (Time=3)	RYD1-BLD1-FF-D3	0.400	0.362	90.68	OK
	RYD1-BLD1-FF-D3	0.400	0.364	91.20	OK
	RYD1-BLD1-FF-E3	0.400	0.359	89.78	OK
	RYD1-BLD1-FF-F3	0.400	0.356	89.16	OK

This study follows the standard IEEE 3002-7 for allowable voltage limits. Based on the study results, all motor terminal voltages are within the permissible limit of 80%, and all bus voltages are within the acceptable limit

C. Harmonics Analysis report

Harmonic analysis was performed to evaluate the distortion levels introduced by nonlinear loads such as UPS systems, Variable Frequency Drives (VFDs), and switch mode power supplies used within the data centre.

The harmonic simulation results indicate that voltage Total Harmonic Distortion (THDv) at critical buses remains within IEEE 519-2022 recommended limits. The dominant harmonic components observed in the system were primarily lower-order harmonics associated with rectifier and inverter-based equipment.

Individual harmonic distortion levels were also analysed and found to be within permissible limits, indicating acceptable harmonic performance of the electrical network.

No significant resonance conditions or abnormal harmonic amplification were observed during simulation. This confirms that the system impedance characteristics and network configuration do not promote excessive harmonic propagation.

The harmonic results validate that the electrical design is suitable for accommodating nonlinear loads commonly present in modern data center environments while maintaining acceptable power quality performance.

Table 6.12: Comparison of Harmonic Distortion Limit

S.No	Bus Name	Bus rated voltage (kV)	THDV%	As per IEEE 519	Status as per IEEE-519
1	Feeder 1	13.8	3.26	<5	With in the Limit
3	Feeder 3	13.8	3.35	<5	With in the Limit
4	T11-OUT-B3	0.4	4.72	<8	With in the Limit
5	T11-OUT-A3	0.4	4.81	<8	With in the Limit
6	T11-OUT-D3	0.4	4.76	<8	With in the Limit
7	T11-OUT-E3	0.4	4.79	<8	With in the Limit
8	T11-OUT-B3	0.4	4.87	<8	With in the Limit
9	T11-OUT-F3	0.4	4.83	<8	With in the Limit

Based on the simulation results, considering all significant harmonic-generating loads such as UPS systems and VFDs in operation, the harmonic distortion levels at the 13.8 kV PCC are found to be within the acceptable limits as prescribed by the IEEE 519-2022 standard.

Hence, the system is operating within the recommended harmonic limits, and no additional mitigation measures are required under the present operating conditions.

V. CONCLUSION

This paper presented a comprehensive power quality assessment of the EDGNEX Data Centre electrical distribution system using ETAP simulation software. The study focused on evaluating the system performance through load flow analysis, motor acceleration analysis, and harmonic distortion assessment under practical operating conditions.

The load flow analysis confirmed that the electrical network maintains acceptable voltage profiles, balanced power distribution, and transformer loading within permissible operating limits under normal steady-state conditions. The results indicate that the designed electrical infrastructure is capable of supplying critical data center loads efficiently while maintaining system stability and operational reliability.

Motor acceleration analysis demonstrated that large induction motors associated with HVAC and cooling systems can be successfully started without causing unacceptable voltage dips or prolonged acceleration periods. Although high inrush current was observed during motor startup, the system exhibited sufficient short-circuit strength and reactive power support to maintain voltage stability and ensure rapid recovery to steady-state conditions.

Harmonic analysis was conducted to evaluate the impact of nonlinear loads such as UPS systems, Variable Frequency Drives (VFDs), and switch mode power supplies commonly present in data centre environments. The simulation results confirmed that voltage Total Harmonic Distortion (THDv) and individual harmonic levels remained within the acceptable limits specified by IEEE 519-2022 standards. No critical resonance conditions or abnormal harmonic amplification were observed in the system.

Based on the simulation outcomes, it can be concluded that the EDGNEX Data Centre electrical distribution system is adequately designed to support both steady-state and transient operating conditions while maintaining acceptable power quality performance, voltage stability, and system reliability.

The results of this study provide valuable technical validation for data centre electrical system design and operation. Future work may include short-circuit analysis, protection coordination studies, arc flash hazard assessment, and reliability analysis to further enhance system safety, operational continuity, and design optimization.

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