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Simulation of Harmonics in Electric Locomotive Power Supply Device

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Abstract An electric locomotive power supply device is responsible for providing electrical power to the traction motors that drive the locomotive. These systems often use alternating current (AC) or direct current (DC) to power the motors, and they can operate using either overhead catenary systems or third-rail power supplies. Simulation of a locomotive power supply device involves analyzing its electrical and mechanical performance, power quality and efficiency. The power electric device which works under condition of high power and heavy load, suffer from faults frequently. The main circuit of the device is a kind of single-phase full bridge half controlled rectifier circuit. Harmonics are higher-frequency components that distort the waveform of current or voltage. In locomotive power supply systems, harmonics are typically introduced by non- linear loads, such as the power electronic devices (inverters, converters) used in these systems. Harmonics can cause several issues, including increased losses, power quality.

Index Terms- Locomotive Power Supply, Traction Motors, Inverters/Converters.

I. INTRODUCTION

An electric locomotive is a locomotive powered by electricity from overhead lines, a third rail or on-board energy storage such as a battery or a super capacitor. Electric locomotives benefit from the high efficiency of electric motors, often above 90% (not including the inefficiency of generating the electricity). Additional efficiency can be gained from regenerative braking, which allows kinetic energy to be recovered during braking to put power back on the line. Newer electric locomotives use AC motor-inverter drive systems that provide for regenerative braking. Electric locomotives are quiet compared to diesel locomotives since there is no engine and exhaust noise and less mechanical noise. The lack of reciprocating parts means electric locomotives are easier on the track, reducing track maintenance. Power plant capacity is far greater than any individual locomotive uses, so electric locomotives can have a higher power output than diesel locomotives and they can produce even higher short-term surge power for fast acceleration.

Harmonics in power supply systems are deviations from the pure sinusoidal waveforms of voltage or current, caused by non-linear loads such as variable frequency drives, LED lighting, and electronic devices. These distortions impact power quality, leading to voltage instability, overheating, and reduced system efficiency. Poor power quality can cause equipment malfunctions, energy losses, and even early failures, resulting in increased operational costs and reliability concerns for power infrastructure.

The presence of harmonics can also amplify resonance effects in the system, causing severe voltage and current distortions that strain components like transformers, motors, and cables. This stress reduces the lifespan of equipment and creates safety risks. Furthermore, harmonics lower the power factor, increasing energy losses and requiring additional reactive power compensation, which raises infrastructure costs. Adhering to harmonic distortion standards is critical to ensure compliance, protect equipment, and maintain system reliability.

Sources of Harmonics in Electric Locomotive Systems
Harmonic distortion in electric locomotives primarily arises from:

- **Power Converters:** AC-DC and DC-AC conversion processes introduce non-linear waveforms.
- **Traction Motors:** Variations in motor operation lead to fluctuating harmonic generation.
- **Regenerative Braking:** Power feedback into the supply network amplifies harmonic content.
- **Unbalanced Loads:** Phase imbalances contribute to harmonic distortions.

Effects of Harmonics on Locomotive Power Systems
Harmonics cause multiple issues, including:
Increased losses and heating in transformers and motors
Voltage instability leading to reduced power quality
Malfunction of sensitive electronic devices
Reduced efficiency and lifespan of electrical components
Potential resonance effects, exacerbating distortions

II. BLOCK DIAGRAM OF POWER SUPPLY DEVICE

Block Diagram of Power Supply Device

25 KV OHE feed to transformer of three phase loco through panto and VCB. The main transformer converts the overhead line voltage (25 kV) to the lower operating voltages. There are four secondary traction windings (two on each converter unit, 1269 V), one for feeding the auxiliary circuits (1000 V) and one for the harmonic filter. The power from transformer secondary goes to line converter. The line converter (NSR) converts the constant frequency AC voltage supplied by the transformer into DC voltage (intermediate link). DC link store the High DC voltage for converting three phase ac. The drive converter (ASR) generates a 3-phase system with variable voltage and frequency from taking DC voltage from DC link. The energy flow is reversed during regenerative braking. Formerly GTO based converter is used but nowadays IGBT based is extensively used in three phase technology. The power elements of the converter unit (line converter, drive converter) are oil-cooled. When braking electrically the traction motors act as generators. In the converter the resulting three-phase electrical energy is converted into single-phase energy which is fed back into the OHE. Output voltage of the Traction converter 2180 V, Output current 831 A, Output power 2365 kW. In a Word single phase, AC supply (OHE)fed in main transformer and it converted D C by line converter (NSR) and store in D C link there after three phase voltage is produced by drive converter (ASR) from DC source for supplying three phase traction motors of locomotive.

Source

The input supply, which is an alternating current (AC) voltage of 1269 volts. It serves as the primary power source for the circuit.

Rectifier

The rectifier converts the AC input voltage into a pulsating DC voltage. This is typically done using diodes (in bridge or full-wave rectifier configurations) that allow current to flow in only one direction.

Filter

The filter smooths the pulsating DC voltage coming from the rectifier into a more stable DC voltage. This is usually achieved using capacitors, inductors, or a combination of both to reduce the ripple in the output voltage.

LC filter with 80–100mF capacitance and 5–10mH inductance effectively reduces ripples in the WAP-7 rectifier circuit

Load: The circuit or device that uses the final DC voltage, which in this case is 800V. The load is electronic device requiring a stable DC voltage for operation.

Passive and Active Filters in Harmonics Mitigation

Passive Filters

Passive filters are simple, cost-effective devices designed to reduce harmonic distortions in electric power systems. These filters consist of reactive components such as inductors (L), capacitors (C), and resistors (R), which are arranged in specific configurations to target and filter out particular harmonic frequencies.

Types of Passive Filters:

- **Shunt Filters:** These filters are connected in parallel with the load and are designed to absorb the harmonic currents. They are typically used for low-order harmonics.
- **Example:** A shunt LC filter can be used to filter the 5th harmonic by tuning the circuit to resonate at that frequency.
- **Series Filters:** These filters are placed in series with the load and block harmonic voltages from reaching sensitive components or other parts of the power system. They are effective for filtering high-frequency harmonics.

Active Filters

Active filters, also known as Active Power Filters (APFs), are more advanced devices that dynamically filter harmonic distortions by injecting compensating currents into the system. Unlike passive filters, which only respond to harmonic frequencies based on their inherent characteristics, active filters continuously monitor the system and adjust their output to provide real-time compensation for harmonic currents.

Types of Active Filters:

- **Shunt Active Filters (Shunt APFs):** These are the most common type of active filters, connected in parallel with the load. They are capable of injecting compensating currents to cancel out the harmonic currents drawn by the load.
- **Example:** A shunt active filter might be used to cancel out the harmonic currents drawn by a traction inverter in an electric locomotive.
- **Series Active Filters (Series APFs):** These filters are connected in series with the load and work to eliminate harmonic voltages in the system. They prevent distorted voltages from affecting the system and sensitive equipment.
- **Example:** A series active filter could be used in a railway system to ensure that the voltage supplied to sensitive onboard equipment remains clean and undistorted.
- **Hybrid Active Filters:** These filters combine the benefits of both passive and active filtering. A hybrid filter typically uses passive filters for low-order harmonics and an active filter for higher-order harmonics.

III. SIMULATION

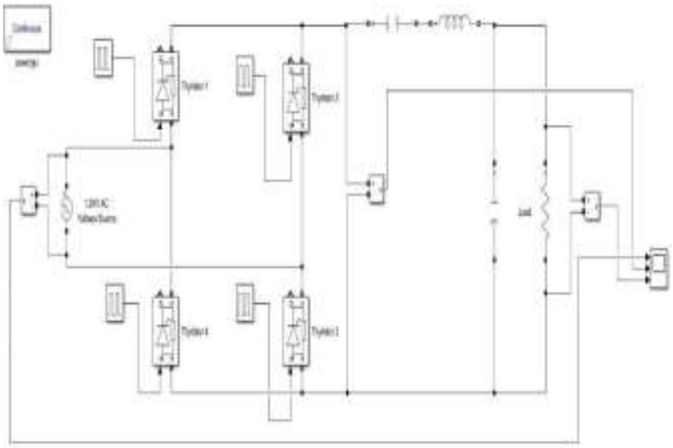

Figure 1: Simulink Model

IV. FUTURE SCOPE

Integration with Advanced Technologies

Artificial Intelligence (AI) and Machine Learning (ML): Future simulations may leverage AI/ML algorithms to predict and mitigate harmonic issues dynamically. These technologies can help optimize system parameters in real- time based on operational data.

DigitalTwinTechnology:
Digital twins of locomotive power supply systems can use real-time data to simulate, monitor, and address harmonic behavior, ensuring optimal system performance.

IoT-BasedMonitoringSystems:
The Internet of Things (IoT) can enhance harmonic simulation by enabling real-time data collection and analysis, improving the accuracy and applicability of simulation results.

Renewable Energy Integration DecarbonizationofRailways:
As railways increasingly adopt renewable energy sources like solar and wind power, harmonic simulation will play a critical role in addressing harmonic distortion caused by variable generation and ensuring seamless integration.

EnergyStorageSystems:
The use of advanced energy storage systems, such as lithium-ion batteries and super capacitors, will require simulation to evaluate their impact on harmonics and optimize their operation.

Advanced Harmonic Mitigation Strategies

CustomFilterDesign
Future research will focus on designing more efficient active and hybrid harmonic filters tailored to specific railway systems, reducing costs and improving system performance.

DynamicCompensationSystems
Adaptive harmonic compensation systems that adjust to varying operating conditions will be simulated and developed for real-time mitigation of harmonics.

Development of High-Speed and Urban Rail Networks

High-SpeedRail
With the expansion of high-speed rail networks worldwide, harmonic simulation will be essential to manage the higher power demands and ensure the stability of power supply systems.

UrbanElectrification
The growth of urban transit systems, including metro and light rail, will necessitate harmonic simulation to optimize power quality in densely populated areas.

Optimization of Multi-System Locomotives

Interoperability AcrossElectrificationSystems:
Multi-system locomotives that operate across regions with different electrification standards (AC and DC) will benefit from simulations that analyze and mitigate harmonics in varying supply environments.

EnergyEfficiencyImprovements
Future simulations will focus on achieving higher energy efficiency in multi-system locomotives by optimizing power conversion and control systems.

SmartGridIntegration
As railways interact more with smart grids, harmonic simulation will be vital to evaluate their impact on grid stability and design systems that prevent harmonic- induced resonance or grid disturbances.

BidirectionalPowerFlow
The increasing use of regenerative braking and energy storage in locomotives will require harmonic simulation to study the effects of bidirectional power flow on both the locomotive and the grid.

V. CONCLUSION

Harmonic analysis employs several analytical techniques to study and mitigate distortions in electrical systems, ensuring optimal performance and compliance with standards. These techniques involve mathematical and computational approaches to evaluate harmonics generated by non-linear loads such as inverters, rectifiers, and variable frequency drives. One of the most fundamental methods is Fourier Analysis, which decomposes complex waveforms into sinusoidal components of different frequencies. By identifying harmonic orders and their amplitudes, Fourier Analysis enables engineers to pinpoint distortion sources and develop mitigation strategies. The Discrete Fourier Transform (DFT) and its computationally efficient variant, the Fast Fourier Transform (FFT), are widely used to analyze time-domain signals and extract frequency-domain characteristics. These techniques are particularly effective for periodic signals and are implemented in tools like MATLAB/Simulink.

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