The Proposal for Implementation of Controlled Power Rectifier (3000/4000KW) in MTA New York City Transit (MTA-NYCT)

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The Proposal for Implementation of Controlled Power Rectifier (3000/4000KW) in MTA New York City Transit (MTA-NYCT) Traction Power System

Thesis submitted in partial fulfillment of the requirement for the degree

Master of Engineering (Electrical)

at

The City College of New York
Of the
City University of New York

By
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May 29, 20015

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The MTA New York City Transit (MTA-NYCT) will require a robust and reconfigurable power system capable of supplying high power in order to be able to provide services based on forecasted future forecast growth of the city population. A critical component in such a system is the Phase Controlled Rectifier. As such, the issues associated with the inclusion of a power electronics rectifier need to be addressed. These issues include input Alternating Current (AC) interface requirements, the output Direct Current (DC) load profile, and overall stability in the output voltage for Train car loads.

Understanding these issues, providing possible solutions and determining the means of assuring smooth compatibility with MTA New York City Transit (MTA-NYCT) Traction Power systems is the focus of this thesis.

By using a Simulink® model of an actual MTA-NYCT Traction Power System, actual train car load, 12 -Pulse count, high power rectifiers were exercised. The Simulink® results are compared between the Traction Power Systems of Uncontrolled Rectifier and Controlled Rectifier analysis results.

In subway normal operation hour, with uncontrolled rectifier systems, subway cars load current level are 2800 Amps to 3600 Amps, and Voltage level 450 VDC to 600 VDC in running condition. In this Simulation, with controlled rectifier system, subway cars load current level are 3200 Amps to 4000 Amps, and Voltage level 550 VDC to 625 VDC established.

These experiments led to the conclusion that increasing the continuous current and the overall stability in the output voltage, reducing the harmonics, there are tradeoffs in terms of complexity and size of the passive components, and optimization based on source and load specifications is also required.
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<td>AC</td>
<td>Alternating Current</td>
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<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>GTO</td>
<td>Gate Turn-Off Thyristor</td>
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<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>LC</td>
<td>Inductor-Capacitor</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>PIC</td>
<td>Programmable Intelligent Computer</td>
</tr>
<tr>
<td>SCR</td>
<td>Silicon Controlled Rectifier</td>
</tr>
<tr>
<td>RCT</td>
<td>Reverse Conducting Thyristor</td>
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<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
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LIST OF RECTIFIER SYMBOLS

The following is a set of letter symbols for use in rectifier circuit analysis and calculation of rectifier characteristics.

\( u \)  
Commutating angle (angle of overlap, sometimes denoted as \( \mu \))

\( \cos(\varphi_1) \)  
Displacement power factor neglecting transformer exciting current

\( \cos(\varphi_1) \)  
Displacement power factor including transformer exciting current

\( \cos(\delta) \)  
Distortion component of power factor

\( D_s \)  
Commutating reactance transformation constant (applies only to the first mode of operation after the light load transition)

\( E_{dx} \)  
Commutating voltage

\( E_F \)  
Total forward voltage drop per circuit element

\( E_{cw} \)  
Crest working voltage

\( E_d \)  
Average direct voltage under load

\( E_{do} \)  
Theoretical direct voltage (average direct voltage at no load or light transition load and zero forward voltage drop)

\( E_{ii} \)  
Initial reverse voltage

\( E_L \)  
Alternating-current system line-to-line voltage

\( E_n \)  
Alternating-current system line-to-neutral voltage

\( E_r \)  
Average direct voltage drop caused by resistance losses in transformer equipment, plus interconnections not included in \( E_F \) (commutating resistance)
$E_s$ Rectifier transformer direct-current (secondary) winding line-to-neutral voltage

$E_x$ Average direct voltage drop caused by commutating reactance

$f$ Frequency of alternating-current power system

$F_x$ $I_cX_e/E_s = \text{commutating reactance factor}$

$h$ Order of harmonic

$I_c$ Direct current commutated in one set of commutating groups

$I_d$ Average rectifier dc load current

$I_e$ Transformer exciting current

$I_g$ Direct current commutated between two rectifying elements in a single commutating group

$I_L$ Alternating line current

$I_{in}$ Equivalent totalized harmonic component of $I_L$

$I_m$ Alternating line current (crest value)

$I_p$ Transformer alternating-current (primary) winding coil current

$I_{pL}$ Alternating line current corresponding to the current in the alternating-current (primary) winding during load loss test in accordance with 8.3.2, Method No. 1

$I_s$ Transformer direct-current winding (secondary) line rms current

$I_{cl}$ Transformer direct-current winding (secondary) coil rms current

$I_1$ Fundamental component of $I_L$

$I_h$ Harmonic component of $I$ of the order indicated by the subscripts

$I_{1P}$ Watt component of $I_1$

$I_{1Q}$ Reactive component of $I_1$
\( K_s \)     Rectifier transformer secondary coupling factor

\( K \)     Ratio of form factor in normal operation to form factor under short circuit conditions

\( L_d \)     Inductance of direct-current reactor in Henrys

\( n \)     Number of simple rectifiers

\( p \)     Number of phases in a simple rectifier

\( P_r \)     Transformer load losses in watts (including resistance and eddy current losses)

\( P_d \)     Output power in watts

\( q \)     Total number of rectifier pulses (pulse number)

\( R_c \)     Line-to-neutral commutating resistance in ohms for a set of commutating groups

\( R_{cn} \)     Equivalent line-to-neutral commutating resistance in ohms for a set of commutating groups referred to the alternating-current winding of a rectifier transformer

\( R_g \)     Line-to-neutral commutating resistance in ohms for a single commutating group

\( R_p \)     Effective resistance of the alternating-current (primary) winding

\( R_s \)     Effective resistance of the direct-current (secondary) winding

\( s \)     Circuit type factor (1 for single way; 2 for double way)

\( X_{cpu} \)     Per unit commutating reactance

\( X_c \)     Line-to-neutral commutating reactance in ohms for a set of commutating groups. This includes the reactance of the rectifier and interconnections for a rectifier unit.

\( X_{cn} \)     Equivalent line-to-neutral commutating reactance in ohms for a set of commutating groups referred to the alternating-current winding (primary) of a rectifier transformer
<table>
<thead>
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>(X_g)</td>
<td>Line-to-neutral commutating reactance in ohms for a single commutating group</td>
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<tr>
<td>(X_L)</td>
<td>Ohms reactance of supply line (per line)</td>
</tr>
<tr>
<td>(X_{Lpu})</td>
<td>Per-unit reactance of supply line, expressed on base of rated volt-amperes at the line terminals of the transformer alternating-current (primary) windings</td>
</tr>
<tr>
<td>(X_{Tpu})</td>
<td>Per-unit reactance of transformer, expressed on base of rated volt-amperes at the line terminals of the transformer alternating-current (primary) windings</td>
</tr>
<tr>
<td>(Z_c)</td>
<td>Line-to-neutral commutating impedance in ohms for a set of commutating groups</td>
</tr>
<tr>
<td>(Z_{cn})</td>
<td>Equivalent line-to-neutral commutating impedance in ohms for a set of commutating groups referred to the alternating-current (primary) winding of a rectifier transformer</td>
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<tr>
<td>(Z_g)</td>
<td>Line-to-neutral commutating impedance in ohms for a single commutating group</td>
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1.0 INTRODUCTION

1.1 Background
A multi-pulse phase controlled rectifier is a type of alternating current (AC) to direct current (DC) converter. This means that it takes an AC voltage source (typically a sinusoid) and changes it into a DC voltage. In reality, the output will be a higher frequency AC waveform with a greatly reduced peak-to-peak voltage that has an average DC value. The term multi-pulse usually applies to three-phase systems and has to do with the fact that there are multiple arch-shaped pulses corresponding to the peak regions of all of the different phase combinations of the source voltages that are seen by the rectifying circuit elements. By using transformers to create phase shifts in the source voltages and connecting these rectifiers together in different fashions, rectifiers with very high pulse counts can be made. A controlled rectifier means that the DC output voltage can be controlled or adjusted in value based on demand, whereas an uncontrolled rectifier will produce a fixed DC output.

A recent and growing trend towards an all Traction Power Systems and the development of integrated power systems has caused the role of these types of rectifiers to become even more important. Due to the ever-increasing rail way transport system with Traction Power requirements without any interruption for normal operation of Subway Car in Public Transport Agency all over the world, the MTA New York City Transit (MTA-NYCT) has a tremendous need for rugged and reliable high power conversion modules in the megawatt range.

In addition to the problem of how to meet all of the power demands caused by these new types of loads, the power electronics (the phase controlled rectifiers) supplying these loads are non-linear. Nonlinear loads produce unwanted harmonic distortion as a byproduct which can negatively affect all directly connected electrical equipment. The phase controlled rectifiers must be able to keep the produced harmonics to an acceptable level and also, be capable of improving the quality of power supply and protect the safety of other equipments.

1.2 Objectives
The main goal of this thesis is to know and determine how effective silicon Controlled Rectifier will improve the transit system operation through simulation and research, because all rectifiers in MTA New York City Transit (MTA-NYCT) Traction Power are uncontrolled power Rectifier. Due to city population growth, there is a high public demand for more subway cars. MTA-NYCT is upgrading the system through fix and forty programs, because few years from now, it’s traction power system has to be able to provide large amount of Power for normal subway operation. MTA NYCT has a plan to replace all Uncontrolled Rectifier by Controlled Rectifier. Under this thesis, the MTA-NYCT Traction Power system are simulated with Uncontrolled Rectifier and Controlled Rectifier and compared between both systems.
2.0 RECTIFIER

2.1 Rectifier Circuit
A rectifying circuit is one, which makes a link between an ac supply to dc load, that is, it converts an alternating voltage supply to a direct voltage. The direct voltage so obtained is not normally leveled, as from a battery, but contains an alternating ripple component superimposed on the mean (dc) level.

The process is known as rectification. Physically, rectifiers take a number of forms, including vacuum tube diodes, mercury-arc valves, copper and selenium oxide rectifiers, semiconductor diodes, silicon-controlled rectifiers and other silicon-based semiconductor switches.

![Figure-2.1: Rectifier Circuit](image)

Rectifiers have many uses, but are often found serving as components of DC power supplies and high-voltage direct current power transmission systems. Rectification may serve in roles other than to generate direct current for use as a source of power. As noted, detectors of radio signals serve as rectifiers. In gas heating systems flame rectification is used to detect presence of a flame.

2.2.0 SINGLE PHASE RECTIFIERS

2.2.1 Uncontrolled Single Phase Rectifier
In half wave rectification of a single-phase supply, either the positive or negative half of the AC wave is passed, while the other half is blocked. One such half-wave rectifier circuit is illustrated in Figure-2.2, where a sinusoidal voltage source is applied to a resistive load through an ideal diode. The diode behaves like a check-valve, only allowing positive AC current to pass through to the resistor. During the negative portion of the source voltage waveform, the diode blocks the current flow, resulting in no voltage drop across the load.
Figure-2.2: Uncontrolled half-wave rectifier circuit with an ideal diode and a resistive load.

Figure-2.3: Source voltage, resistor voltage, and current waveform profiles for an Uncontrolled halfwave rectifier circuit.
2.2.2 Uncontrolled Single-Phase Full-Wave Rectifier
A full-wave rectifier is the next logical progression beyond a half-wave rectifier. A simple full-wave rectifier (sometimes called a bridge rectifier) with a resistive load is shown in Figure-2.4.

Figure-2.4: Uncontrolled full-wave rectifier circuit with ideal diodes and a resistive load.

In this circuit, the source voltage and load resistor are identical to those of the half-wave rectifier case. In the full-wave rectifier circuit, in addition to the current that flows during the positive portion of the source voltage waveform, current will also flow during the negative portion due to the second pair of diodes. During the positive portion of the source voltage waveform, diodes $D_1$ and $D_4$ are “on” while diodes $D_2$ and $D_3$ are “off,” and current will flow in the direction indicated by the load current $i_L$. During the negative portion of the source voltage waveform, diodes $D_1$ and $D_4$ are “off” while diodes $D_2$ and $D_3$ are “on.”
2.3.0 CONTROLLED SINGLE-PHASE RECTIFIERS

2.3.1 Controlled Single-Phase Half-Wave Rectifier
If the diode from the circuit of Figure-2.2 is replaced with a thyristor or silicon controlled rectifier (SCR), the result is a controlled half-wave rectifier of Figure-2.6. The SCR behaves similarly to a diode in that it is a one-way device and will block current flow in the negative direction. However, it will not conduct in the forward direction until an appropriate trigger signal has been applied to its gate [10]. In reality, there will be a short delay before the SCR turns “on” even after it has been adequately triggered; but for the purpose of explanation, the SCR in Figure-2.5 can be considered ideal and will turn “on” immediately when triggered. The angle at which the SCR is triggered is commonly called the firing angle $\alpha$. If the SCR in Figure-2.5 is triggered at time $t_1$, which is equal to $\alpha/\omega$ (where $\omega$ is the radian frequency), the resistor voltage and current will be as shown in Figure-2.7.
Figure-2.6: Controlled half-wave rectifier circuit with an ideal SCR and a resistive load.

Figure-2.7: Source voltage, load voltage, and load current waveform profiles for a Controlled half-wave rectifier circuit triggered at time \( t_1 \).
2.3.2. Controlled Single-Phase Full-Wave Rectifier

By replacing the diodes in Figure-2.4 with SCRs, a controlled full-wave rectifier is created as shown in Figure-2.8. SCRs are gated in pairs with the firing angle $\alpha$ again corresponding to time $t_1 = \alpha/\omega$. During the positive portion of the source voltage waveform, all SCRs are initially “off” until SCR$_1$ and SCR$_4$ are gated “on” while SCR$_2$ and SCR$_3$ remain “off” due to being reverse biased. During the negative portion of the source voltage waveform, the opposite situation occurs and all SCRs are “off” until SCR$_2$ and SCR$_3$ are gated “on” while SCR$_1$ and SCR$_4$ remain reverse biased and “off.” The resulting current yields zero voltage drop across the load resistor during the time the SCRs are “off” and a positive load voltage drop during both the positive and negative portions of the source voltage waveform when the appropriate SCRs have been gated “on.” Profiles of the source voltage, source current, load voltage, and load current as just described are illustrated in Figure-2.9.

![Figure-2.8: Controlled full-wave rectifier circuit with ideal SCRs and a resistive load.](image-url)
Figure-2.9: Source voltage, source current, load voltage, and load current waveform Profiles for a controlled full-wave rectifier circuit triggered at time $t_1$. $t_2 = t_1 + T/2$. 
3.0 THREE PHASE UNCONTROLLED RECTIFIER

3.1.0 Definition
Single-phase rectifiers are commonly used for power supplies for domestic equipment. However, for most industrial and high-power applications, three-phase rectifier circuits are the norm. As with single-phase rectifiers, three-phase rectifiers can take the form of a half-wave circuit, a full-wave circuit using a center-tapped transformer, or a full-wave bridge circuit.

3.1.1 Three Phase Uncontrolled Rectifier Circuit
Figure-3.1. Series circuit arrangement for a 12-pulse rectifier using a wye-delta and delta-delta connected transformer to achieve the necessary 30° phase shift between 6-pulse rectifier units. From while it was relatively simple to realize the 12-pulse rectifier by taking advantage of the 30° Phase shift that naturally occurs for a wye-delta transformer.

Figure-3.1: 12-Pulse uncontrolled Rectifier Circuit
3.2.0 Basic Rectifier Components and Equipment

3.2.1 Anode terminal: The anode terminal of a rectifier diode or rectifier stack is the terminal to which forward current flows from the external circuit. In the semiconductor rectifier components field, the anode terminal is normally marked "negative."

3.2.2 Cathode terminal: The cathode terminal of a rectifier diode or rectifier stack is the terminal from which forward current flows to the external circuit. In the semiconductor rectifier components field, the cathode terminal is normally marked "positive."

3.2.3 Forward direction: The forward direction of a rectifier diode is the direction of lesser resistance to steady direct-current flow through the diode; for example, from anode to cathode.

3.2.4 Rectifier: An integral assembly of semiconductor rectifier diodes or stacks including all necessary auxiliaries such as cooling equipment, current balancing, voltage divider, surge suppression equipment, etc, and housing, if any.

3.2.5 Power converter: As used in this standard, an assembly of semiconductor devices or device stacks, including all necessary auxiliaries, for the purpose of changing alternating-current power to direct-current power.

3.2.6 Power rectifier: A rectifier unit in which the direction of average energy flow is from the alternating-current circuit to the direct-current circuit.

3.2.7 Rectifier diode: A semiconductor diode having two electrodes and an asymmetrical voltage-current characteristic, used for the purpose of rectification, and including its associated housing, mounting, and cooling attachments if integral with it.

3.2.8 Reverse direction: The reverse direction of a rectifier diode is the direction of greater resistance to steady direct-current flow through the diode; for example, from cathode to anode.

3.2.9 Rectifier junction: The portion of a rectifier diode that exhibits an asymmetrical current voltage characteristic.

3.2.10 Rectifier stack: An integral assembly, with terminal connections, of two or more semiconductor rectifier diodes, and includes its associated housing and any associated mounting and cooling attachments.

3.2.11 Rectifier unit: An operative assembly consisting of the rectifier, or rectifiers, together with the rectifier auxiliaries, the rectifier transformer equipment, and interconnecting circuits/bus work. A frequently used alternate expression is transformer rectifier unit.
3.2.12 **Reaction of rectifier unit:** A section of a rectifier unit is a part of a rectifier unit, including its auxiliaries, which is capable of independent operation.

3.3.0 **Appurtenances and Auxiliaries**

3.3.1 **Cooling system (of a rectifier):** The equipment, i.e., parts and their interconnections, used for cooling a rectifier. It includes all or some of the following: rectifier water jacket, cooling coils or fins, heat exchanger, blower, water pump, expansion tank, insulating pipes, etc.

3.3.2 **Current balancing reactors:** Reactors used in rectifiers to force satisfactory division of current among parallel connected rectifier bridges, phases or diodes.

3.3.3 **Diode failure detector:** A device or system to indicate the failure of one or more diodes. This function is normally performed by monitoring the failure of a fuse associated with the failed diode: (1) visually, by a mechanical device or light on each fuse, (2) by a summary contact associated with any fuse failure, or (3) by a two stage system in which the second stage is from a second failure in the same element.

3.3.4 **Diode fuses:** Diode fuses are fuses of special characteristics connected in series with one or more semiconductor rectifier diodes to disconnect the semiconductor rectifier diode in case of failure and protect the other components of the rectifier.

3.3.5 **Forced air cooling system:** An air cooling system in which heat is removed from the cooling surfaces of the rectifier by means of a flow of air produced by a fan or blower.

3.3.6 **Heat exchanger cooling system (of a rectifier):** A cooling system in which the coolant, after passing over the cooling surfaces of the rectifier, is cooled in a heat exchanger and recirculated.

3.3.7 **Heat sink:** The heat sink of a rectifier diode is a mass of metal generally having much greater thermal capacity than the diode itself, and intimately associated with it. It encompasses that part of the cooling system to which heat flows from the diode by thermal conduction only, and from which heat may be removed by the cooling medium.

3.3.8 **Interphase transformer:** A transformer or reactor that introduces commutating inductance between parallel connected simple rectifiers units. Its purpose is to enable paralleled rectifier units to operate essentially independently at 120° conduction angle.
3.3.9 **Natural air cooling system:** An air cooling system in which heat is removed from the cooling surfaces of the rectifier only by the action of the ambient air through convection.

3.3.10 **Reverse voltage dividers:** Devices employed to assure satisfactory division of reverse voltage among series connected semiconductor rectifier diodes. Transformers, bleeder resistors, capacitors, or combinations thereof, may be employed.

3.3.11 **Temperature regulating equipment:** Any equipment used for heating and cooling the rectifier, together with the devices for controlling and indicating its temperature.

3.3.12 **Voltage surge suppressors:** Devices used in the rectifier to attenuate surge voltages of internal or external origin. Capacitors, resistors, nonlinear resistors, or combinations thereof, may be employed. Nonlinear resistors include electronic and semiconductor devices.

3.4.0 **Semiconductor Rectifier Diode Characteristics**

3.4.1 **AC rms voltage rating:** The ac rms voltage rating is the maximum rms value of applied sinusoidal voltage.

3.4.2 **Average forward current:** The average forward current rating is the maximum average value of forward current averaged over a full cycle.

3.4.3 **Crest working voltage:** The crest working voltage between two points is the maximum instantaneous difference of voltage, excluding oscillatory and transient over voltages, which exists during normal operation.

3.4.4 **DC blocking voltage rating:** The dc blocking voltage rating is the maximum continuous dc reverse voltage.

3.4.5 **Forward power loss:** The power loss within a semiconductor rectifier diode resulting from the flow of forward current.

3.4.6 **Forward slope resistance:** The value of resistance calculated from the slope of the straight line used when determining the threshold voltage.

3.4.7 **Forward voltage drop:** The forward voltage drop is the voltage drop in a semiconductor rectifier diode or stack resulting from the flow of forward current.

3.4.8 **Initial reverse voltage:** The instantaneous value of the reverse voltage which occurs across a rectifier circuit element immediately following the conducting period and including the first peak of oscillation.
3.4.9 Maximum surge current (non-repetitive): The maximum surge current is the maximum peak forward current having a specified wave form and short specified time interval.

3.4.10 Non-repetitive peak reverse voltage: The maximum instantaneous value of the reverse voltage, including all non-repetitive transient voltages but excluding all repetitive transient voltages, which occurs across a semiconductor rectifier diode or stack.

3.4.11 Peak forward current (repetitive): The peak forward current is the maximum repetitive instantaneous forward current. It includes all repetitive transient currents but excludes all non-repetitive transient currents.

3.4.12 Recovery charge: The total amount of charge recovered from a diode, including the capacitive component of charge, when the diode is switched from a specified conductive condition to a specified nonconductive condition with other circuit conditions as specified.

3.4.13 Repetitive peak reverse voltage (PRV): The maximum instantaneous value of the reverse voltage, including all repetitive transient voltages but excluding all nonrepetitive transient voltages, which occurs across a semiconductor rectifier diode or stack.

3.4.14 Reverse power loss: The power loss within a semiconductor rectifier diode resulting from the flow of reverse current.

3.4.15 Reverse recovery current: The transient component of reverse current of a rectifier diode associated with a change from forward conduction to reverse blocking.

3.4.16 Threshold voltage: The threshold voltage is the zero-current voltage intercept of a straight line approximation of the forward current-voltage characteristic over the normal operating range.

3.4.17 Total power loss: The sum of the forward and reverse power losses.

3.4.18 Virtual junction temperature: A calculated temperature within the semiconductor material which is based on a representation of the thermal and electrical behavior of a rectifier diode.

3.4.19 Working peak reverse voltage: The peak reverse voltage excluding all transient voltages.
3.5.0 Rectifier Circuit Properties and Terminology

3.5.1 Base load resistor: A resistor connected as a load on the rectifier for the purpose of lowering the no-load voltage by magnetizing the interphase transformer. The value of this resistor is dependent on the current required to magnetize the interphase transformer.

3.5.2 Cascade rectifier: a rectifier in which two or more simple rectifiers are connected in such a way that their direct voltages add, but their commutations do not coincide.

3.5.3 Commutation: Commutation is the transfer of unidirectional current between rectifier circuit elements that conduct in succession.

3.5.4 Commutation factor: The commutation factor for a rectifier circuit is the product of the rate of current decay at the end of conduction, in amperes per microsecond, and the initial reverse voltage in kilovolts.

3.5.5 Commutating angle (\(u\)): The time, expressed in electrical degrees, during which the current is commutated between two rectifier circuit elements. It is also referred to as the angle of overlap.

3.5.6 Commutating group: A group of rectifier circuit elements and the alternating-voltage supply elements conductively connected to them in which the direct current of the group is commutated between individual elements which conduct in succession.

3.5.7 Commutating reactance (\(X_c\)): Commutating reactance is the reactance which effectively opposes the transfer of current between rectifier circuit elements of a commutating group, or set of commutating groups. Commutating reactance includes source, rectifier transformer, and rectifier ac bus reactance.

3.5.8 Commutating reactance factor (\(F_x\)): The line-to-neutral commutating reactance in ohms, multiplied by the commutated direct-current, and divided by the effective (root-mean square) value of the line-to-neutral voltage of the rectifier transformer direct-current winding, or \(\frac{I_c X_c}{E_s}\). A dimensionless quantity, it is often referred to simply as the “reactance factor”. It is used primarily to characterize the mode of operation of a rectifier.

3.5.9 Commutating reactance transformation constant (\(D_x\)): A constant used in transforming line-to-neutral commutating reactance in ohms on the direct-current rectifier transformer winding to equivalent line-to-neutral reactance in ohms referred to the alternating current winding.
3.5.10 **Commutating voltage** ($E_{dA}$): The phase-to-phase ac voltage of a commutating group.

3.5.11 **Conducting period**: That part of an alternating-voltage cycle during which the current flows in the forward direction.

3.5.12 **Double-way rectifier**: A rectifier in which the current between each terminal of the alternating-voltage circuit and the rectifier circuit elements conductively connected to it flows in both directions.

3.5.13 **Full-wave rectifier**: A rectifier which changes single-phase alternating current into pulsating unidirectional current, utilizing both halves of each cycle.

3.5.14 **Half-wave rectifier**: A rectifier which changes single-phase alternating current into pulsating unidirectional current, utilizing only one-half of each cycle.

3.5.15 **Light transition load**: The light transition load is the load at which the interphase transformer (IPT) is magnetized, and the terminal voltage falls on the inherent regulation curve. The light transition load is dependent on the IPT characteristics and is typically less than 3 percent.

3.5.16 **Light load resistor**: A high value resistor connected as a load on the rectifier for the purpose of discharging the no load voltage increase due primarily to system capacitance.

3.5.17 **Loosely coupled**: A rectifier transformer with coupling factor $K_s \leq 0.25$.

3.5.18 **Mode of operation**: The mode of operation of a rectifier circuit is the characteristic pattern of operation determined by the sequence and duration of commutation and conduction.

3.5.19 **Multiple rectifier**: A rectifier in which two or more simple rectifiers are connected in such a way that their direct currents add, but their commutations do not coincide.

3.5.20 **Parallel rectifier**: A rectifier in which two or more simple rectifiers are connected in such a way that their direct currents add and their commutations coincide.

3.5.21 **Phase number** ($p$): The number of ac circuits connected to the rectifier that have nominally equal voltage magnitudes and frequencies but different phase angles. For example, 6 pulse double way rectifiers have a phase number of 3, whereas 12 pulse double way rectifiers have a phase number of 6.

3.5.22 **Pulse number** ($q$): The total number of successive, non-simultaneous commutations occurring within that rectifier circuit during each cycle when operating without phase control. It is also equal to the order of the principal harmonic in the direct voltage, that is, the number of pulses present in the dc output voltage during one cycle of the supply voltage.
3.5.23 **Rectifier circuit element**: A group of one or more semiconductor rectifier diodes, connected in series or parallel or any combination of both, bounded by no more than two circuit terminals, and conducting forward current in the same direction between these terminals.

3.5.24 **Rectifier transformer secondary coupling factor** \((K_s)\): An expression of the degree of mutual coupling between the secondary windings of a three-winding rectifier transformer. \(K_s = 0\) signifies fully uncoupled secondaries, and is equivalent to the coupling of two separate twowinding transformers. The transformer \(K_s\) factor has a major impact on the voltage regulation and short circuit current of a rectifier unit.

3.5.25 **Reverse period**: The reverse period of a rectifier circuit element is that part of an alternating-voltage cycle during which the current flows in the reverse direction.

3.5.26 **Series rectifier**: A rectifier in which two or more simple rectifiers are connected in such a way that their dc voltages add and their commutations coincide.

3.5.27 **Set of commutating groups**: A set of commutating groups consists of two or more commutating groups which have simultaneous commutations.

3.5.28 **Simple rectifier**: A rectifier consisting of one commutating group of single-way, or two commutating groups if double-way.

3.5.29 **Single-way rectifier**: A rectifier in which the current between each terminal of the alternating-voltage circuit and the rectifier circuit element or elements conductively connected to it flows only in one direction.

3.5.30 **Transition load**: The load at which a rectifier changes from one mode of operation to another.

3.6.0 **Rectifier Characteristics**

3.6.1 **Bridge current unbalance**: A calculation that describes the variation of current among rectifier bridge circuits for multi-bridge rectifier designs. Expressed as a percent, it is the maximum deviation of one bridge current from the average of all bridge currents, divided by the average bridge current.

3.6.2 **Diode current unbalance**: An expression of the degree to which currents flowing in parallel diodes are unequal. Expressed as a percent, the diode unbalance for individual diodes equals \(100\% \times (\text{individual diode current} – \text{average diode current}) / \text{average diode current}\), where the average diode current is the average of all the currents flowing through parallel diodes.
3.6.3 **Displacement power factor:** The displacement component of power factor is the ratio of the active power of the fundamental wave, in watts, to the apparent power of the fundamental wave in volt-amperes (including the exciting current of the rectifier transformer).

3.6.4 **Distortion power factor:** The current and/or voltage harmonic distortion-influenced component of the total power factor.

3.6.5 **Efficiency:** The efficiency of a rectifier, or a rectifier unit, is the ratio of the power output to the total power input at a specified value of load.

3.6.6 **Form factor:** The form factor of a periodic function is the ratio of the rms value to the average absolute value, averaged over a full period of the function.

3.6.7 **Harmonic content:** The harmonic content of a non-sinusoidal periodic wave is its deviation from the fundamental sinusoidal form.

3.6.8 **Inherent voltage regulation:** The inherent voltage regulation of a rectifier unit is the change in output voltage, expressed in volts, that occurs when the load is reduced from some rated value of current to zero, or to light transition load for multiple rectifier circuits, with rated sinusoidal voltage applied to the ac line terminals, with the rectifier transformer on the rated tap, excluding the effect of ac system impedance, and the corrective action of any automatic voltage regulation means, but not its impedance. Inherent voltage regulation is based on the impedance of the rectifier, the rectifier transformer, and the interconnecting circuits.

3.6.9 **Phase current unbalance:** A calculation that describes the variation of current among each of the rectifier’s alternating current phases. When calculated in terms of current magnitudes, it is the maximum deviation of one phase current from the average of all phase currents, divided by the average phase current.

3.6.10 **Power factor (total):** The ratio of the total power input, in watts, to the total volt-ampere input to the rectifier unit, at a specified value of load.

3.6.11 **Ripple amplitude:** The maximum value of the instantaneous difference between the average and instantaneous values of a pulsating unidirectional wave.

3.6.12 **Ripple voltage or current:** The alternating component whose instantaneous values are the difference between the average and instantaneous values of a pulsating unidirectional voltage or current.
3.6.13 **rms ripple:** The RMS effective value of the instantaneous difference between the average and instantaneous values of a pulsating unidirectional wave integrated over a complete cycle.

3.6.14 **Total voltage regulation:** The total voltage regulation of a rectifier unit is the change in output voltage, expressed in volts, that occurs when the load current is reduced from some rated value of current to zero, or light transition load for multiple rectifier circuits, with rated sinusoidal alternating voltage applied to the alternating-current line terminals. It includes the effect of the alternating-current system source impedances as seen from the rectifier primary terminals as if they were inserted between the line terminals and the transformer, with the rectifier transformer on the rated tap, but excluding the corrective action of any automatic voltage regulating means, but not its impedance.

3.6.15 **Voltage regulation:** The voltage regulation of a semiconductor rectifier, or rectifier unit, is the change in output voltage that occurs when the load is reduced from a rated value of load current to no load, or to light transition load for multiple rectifier circuits, with all other quantities remaining unchanged. Since the rated load current value may differ from 100% rated load, the load range associated with a particular voltage regulation value shall be provided. When expressed as a percent, voltage regulation equals $100\% \times \frac{\text{voltage at light transition load} - \text{voltage at the rated load}}{\text{voltage at rated load}}$.

3.6.16 **Voltage unbalance:** A calculation that describes the variation of voltage among each of the rectifier’s alternating current phases. When calculated in terms of voltage magnitudes, it is the maximum deviation of one phase voltage from the average of all phase voltages, divided by the average phase voltage. Voltage input unbalance creates current unbalance in the rectifier and rectifier transformer, additional harmonic currents, and complicates interphase transformer design.

3.7.0 **Rectifier Unit Ratings**

3.7.1 **Continuous rating of a rectifier unit:** The continuous rating of a rectifier unit defines the maximum load which can be carried continuously without exceeding established temperature rise limitations under prescribed conditions of test, and within the limitations of established standards.

3.7.2 **Rated alternating voltage:** The rated alternating voltage of a rectifier unit is the rms voltage between the alternating-current line terminals which is specified as the basis for rating.

3.7.3 **Rated load of a rectifier unit:** The kilowatt power output which can be delivered continuously at the rated output voltage. It may also be designated as the 100 percent load or full load rating of the unit.
3.7.4 Rated output current of a rectifier unit: The rated output current of a rectifier unit is the current derived from the rated load and the rated output voltage. The rated current value is to be referred to as the 100% value.

3.7.5 Rated output voltage of a rectifier unit: The rated output voltage of a rectifier unit is the voltage specified as the basis of rating. It is the average value of the direct voltage between dc terminals of the assembly or equipment at rated direct current.

3.7.6 Rated value: A specified value for the electrical, thermal, mechanical and environmental quantities assigned by the manufacturer to define the operating conditions under which a diode, diode stack, assembly or rectifier is expected to provide satisfactory service. NOTE - Unlike many other electrical components, semiconductor devices may be irreparably damaged within very short time intervals when operated in excess of maximum rated values.

3.7.7 Rating of rectifier unit: The rating of a rectifier unit is the kilowatt power output, voltages, currents, number of pulses, frequency, etc, assigned to it by the manufacturer.

3.7.8 Short-time rating of a rectifier unit: The short-time rating of a rectifier unit defines the maximum load which can be carried for a specified short time, without exceeding the specified temperature rise limitations under prescribed conditions of test, and within the limitations of established standards.

3.7.9 Rectifier Protective Device Numbers
Table 3.1 below lists electrical devices commonly used in rectifier assemblies and their corresponding device numbers. These device numbers have not been formally standardized and their usage may vary slightly between operating agencies.
### TABLE 3.1: Rectifier Protective Device number

<table>
<thead>
<tr>
<th>Number</th>
<th>Protective Device Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>26R1</td>
<td>Rectifier diode over temperature – 1(^{st}) stage</td>
</tr>
<tr>
<td>26R2</td>
<td>Rectifier diode over temperature – 2(^{nd}) stage</td>
</tr>
<tr>
<td>33X</td>
<td>Rectifier enclosure door open</td>
</tr>
<tr>
<td>57G</td>
<td>Grounding device</td>
</tr>
<tr>
<td>63A</td>
<td>Rectifier low air flow (forced-cooled only)</td>
</tr>
<tr>
<td>64</td>
<td>Rectifier enclosure energized – trip</td>
</tr>
<tr>
<td>64G</td>
<td>Rectifier enclosure grounded - alarm</td>
</tr>
<tr>
<td>89N</td>
<td>Rectifier negative pole disconnect switch</td>
</tr>
<tr>
<td>98A</td>
<td>Rectifier diode failure – 1(^{st}) stage</td>
</tr>
<tr>
<td>98T</td>
<td>Rectifier diode failure – 2(^{nd}) stage</td>
</tr>
<tr>
<td>99A</td>
<td>Rectifier surge protection failure</td>
</tr>
</tbody>
</table>

#### 3.8.0 Uncontrolled Rectifier Circuits

#### 3.8.1 General

Figure-3.1 includes rectifier circuits with standard diagrams, approved names, and identifying numbers. The circuit diagrams in Figure 1 are voltage vector diagrams and show standard terminal markings, phase relations, and direct-current winding voltage. The terminal markings and phase relations are so selected that phase $R_i$ is either in phase with $H_i$ to neutral or lags $H_i$ by the minimum amount. This table does not imply that other rectifier configurations may not be used.

Rectifier circuit nomenclature is based on descriptive name given in the following order:

- The connection of the transformer alternating-current windings
- The number of pulses of the rectifier unit;
- The connection of the transformer direct-current windings and rectifying elements; and
- Type of circuit (single-way or double-way). In describing multiple rectifiers, the prefixes double, triple, and quadruple are used to indicate the number of component simple rectifiers, and the names diametric, wye, cross, star, fork, zig-zag, aster, etc, are used to denote the connection of each component simple rectifier.
3.8.2 Uncontrolled Rectifier Circuits

Figure-3.1: Uncontrolled Rectifier Circuits
3.9.0 Ratings of Uncontrolled Rectifier

3.9.1 Heavy Traction Service
The standard rating of a rectifier unit for heavy traction service is as follows:
100 percent rated load amperes continuously until constant temperatures have been reached by all parts of the rectifier unit, followed by either 150 percent current for 2 hours following 100 percent load or 300 percent current for 1 minute.

3.9.2 Extra Heavy Traction Service
The standard rating of a rectifier unit for extra heavy traction service is as follows (refer to Figure-3.2 below which can also be found in the former NEMA Standard RI 9):

100 percent rated load amperes continuously until constant temperatures have been reached by all parts of the rectifier unit, followed by 150 percent current for 2 hours and a superimposed cycle of overloads consisting of five periods of 1 minute each at 300 percent of rated load amperes, followed by one period of 450 percent of rated load amperes for 15 seconds at the end of the period. These periods shall be evenly spaced throughout the 2 hour period.

Figure-3.2: Heavy Traction Power Service
3.9.3 Custom Rating (Load Cycle)
A custom rating may be defined for load cycles not reasonably covered in the standard load cycles defined above. This could include cycles defined by simulation results and international or foreign rectifier standards (for example IEC 60146-1-1). It is noted that the standard load cycles will typically provide long term and transient characteristics of the rectifier that can be used for assessment of any load (thermal) cycle.

3.9.4 Operation above Rated Voltage
The rectifier unit shall be capable of operating under the following conditions:

- 10 percent above rated voltage on the transformer alternating-current winding at no load.
- 5 percent above rated voltage on the transformer alternating-current winding at 5 percent below rated output current.
- The ratio of diode peak reverse voltage (PRV) to crest working voltage shall be based on rated direct-current (secondary) winding voltage unless voltage conditions more severe than (a) and (b) are specified.

3.10.0. Performance Characteristics

3. 10.1 Efficiency and Losses

3. 10.1.1 Efficiency Determination
The efficiency of a rectifier unit shall be determined by calculation for rated voltages, currents, and frequency based upon separately measured or calculated losses in the various components of the rectifier unit, and for the normal mode of operation obtained with the specified rectifier transformer connection. Rated direct voltage shall be assumed in determining the efficiencies at all loads. The efficiency of a rectifier unit provided with transformer taps for adjusting the output voltage shall be based on the tap designed to produce rated output voltage, unless efficiencies at other voltages are specified. Efficiency determination shall be made at loads for which efficiency values are specified.

3. 10.1.2 Classification of Losses
The following losses shall be included when calculating the efficiency of a single rectifier unit or multiple units supplying a common load:

- Losses in diodes, fuses, busbars, cables, connectors, potential dividers, and diode current balancing devices
- Losses in surge absorbing equipment
- Power absorbed by fans or pumps for moving the cooling media through the cooling system of the rectifier, whether or not these devices are integrally mounted in the rectifier
- Losses in controls, monitors and indication equipment directly related to the proper functioning of the rectifier
• Losses in rectifier transformer and interphase transformers
• Losses in ac current limiting and balancing reactors
• Losses in dc inductors

3. 10.2 Rectifier Losses
The forward power loss includes all forward losses in the circuit elements and their connections. For rectifiers in the voltage class addressed in this standard, most of this loss is generated in the forward drop of the diodes. This loss is approximately equal to the product of the forward voltage drop, averaged over the conducting period, and the average forward current.

Forward power losses, if required for efficiency determination, shall be obtained by measurement in accordance Test Procedures. Reverse current power losses in voltage divider resistors may be measured or computed.

3. 10.3. Auxiliary Losses
Auxiliary losses to be included in efficiency determinations are the losses in those auxiliaries which operate continuously, unless specifically excepted, as follows:
• Blower and motors if used continuously.
• Relaying, metering, indication & control devices taking significant power.
• Isolating transformers.

3. 10.4 Special Losses
a) The losses in equipment listed below are to be included in the efficiency determination of a rectifier unit if serving only that unit, or in the overall efficiency determination of a multiple unit installation serving a common load, if they serve all of them.

• Wave-filtering equipment such as reactors or resonant shunts
• Current limiting reactors
• Auxiliary and control power transformers or sensors necessary for rectifier operation

b) Losses in equipment below are not to be included in the efficiency determination. The losses in such equipment, under various operating conditions, shall be stated separately by the manufacturer.

• Light-load voltage rise suppressing equipment, unless permanently connected
• Dynamic braking equipment
• Special loads which may be taken off between the transformer and rectifier
• Other special equipment
3.11.0 Voltage Regulation

3.11.1 Determination of Inherent Voltage Regulation.
For an uncontrolled rectifier, the direct voltage $E_d$ at the specified load current $I_d$ is $E_{d0}$ minus the voltage regulation in Volts, or

$$E_d = E_{d0} - E_r - (s \times E_F) - E_x$$  \hspace{1cm} (3.1)

where
- $E_{d0}$ is the direct (dc) no-load or light transition load voltage
- $E_r$ is the direct voltage drop due to circuit (commutating) resistances $s$ is the circuit type factor (single-way or double-way)
- $E_F$ is the total forward voltage drop per circuit element (diode group) $E_x$ is the direct voltage drop due to commutating reactance.

$$E_{d0} = s \times \sqrt{2} \times E_s \times (p / \pi) \times \sin(\pi / p) = C \times E_s$$  \hspace{1cm} (3.2)

where
- $E_s$ is the rectifier transformer secondary winding line-to-neutral voltage
- $p$ is the number of rectifier phases.
For three-phase, double-way 6-pulse and 12-pulse rectifiers, the value of the constant $C$ is $3 \sqrt{6} / \pi$ or 2.3391.

$$E_r = P_r / I_d + E_B$$  \hspace{1cm} (3.3)

where
- $P_r$ is the resistive load loss in the rectifier transformer
- $E_B$ is the resistive voltage drop in the circuit conductors interconnecting the rectifier and rectifier transformer, and the circuit elements within the rectifier (busbars, connectors, fuses, etc.).

$E_F$ is the forward voltage drop across the diodes in a rectifier phase leg. $E_F$ is often characterized as two components, a constant forward-bias junction diode voltage $V_o$ and a current-dependent voltage. The current-dependent term can be approximated by $R_o \times I$, where $R_o$ is the diode forward resistance and $I$ is the current through one diode. $V_o$ and $R_o$ are typically obtained from diode manufacturer data. In the normal load and overload range, $V_o$ accounts for a very large portion of the diode drop, and the diode drop can be considered constant for regulation calculations.

$$E_x = (s \times p / 2 \pi) \times I_c \times X_c$$  \hspace{1cm} (3.4)
where

$s$ is the circuit type factor (single-way or double-way)
$p$ is the number of rectifier phases
$I_c$ is the direct current commutated in one set of commutating groups, in Amperes
$X_c$ is the line-to-neutral commutating reactance for a set of commutating groups, in Ohms

This expression is normally valid for typical loading conditions encountered in traction service. For heavy overloads or short circuit conditions, the voltage drop due to commutating reactance becomes a much more complicated expression that varies with rectifier pulse number, commutating angle, and the degree of coupling between rectifier transformer secondary windings.

Utilize the commutating reactance factor $F_x = I_c X_c / E_s$ to determine and to differentiate between rectifier modes of operation for loads in excess of 100%.

### 3.11.2 6-Pulse Double-Way Rectifiers

6-pulse double-way rectifiers exhibit three modes of operation between no load and short circuit. For operation up to 450% rated load with an inductive load that is typical for traction power applications, however, only mode one need normally be considered. Mode one is characterized by reactance factors ranging from zero to $6/4$ or 0.6214 for inductive loads (this corresponds to commutating angles varying from 0 to 60 degrees). In this range, the following expression may be used to calculate the direct voltage drop due to commutating reactance, $E_x$:

$$E_x = \frac{1}{\sqrt{6}} \times E_{do} \times F_x$$

where

$E_{do}$ is the direct (dc) no-load or light transition load voltage
$F_x$ is the commutating reactance factor

### 3.11.3 12-Pulse Double-Way Rectifiers with Interphase Transformers

12-pulse double-way rectifiers with interphase transformers exhibit five modes of operation between no load and short circuit. These dual-bridge rectifier circuit configurations 31, 31A and 31C are connected to different secondary windings on the same rectifier transformer. Current flow in these windings may cause them to influence each other through their mutual reactance. The coupling factor $K_s$ represents the degree to which the transformer secondary windings interact. A coupling factor $K_s$ of zero represents secondary windings that are on entirely separate cores (no mutual coupling). The direct voltage due to commutating reactance $E_x$ for a 12-pulse double-way rectifier with a $K_s$ of zero is the same as $E_x$ for the six-pulse rectifier noted in 3.11.2 above for the same reactance factor range.
When $K_s > 0$, however, the commutating reactance varies with $K_s$, which greatly complicates calculation of $E_x$.

For $K_s > 0$, $E_x$ may be obtained from Equation (3.5) when $F_x$ is between zero and 0.1641 (12-pulse mode 1). For values of $F_x$ greater than 0.1641, $E_x$ may be calculated from the various equations in Witzke, Kesser and Dillard [B9]. Alternatively, the corresponding value of $E_d/E_{do}$ may be obtained from Fig. 3.1 in [B9], which has been reproduced in Figures 3.3 and 3.4 below.

Using this method,

$$E_x = E_{do} x (1 - E_d / E_{do})$$

(3.6)

where

$E_{do}$ is the direct (dc) no-load or light transition load voltage

$E_d$ is the average direct voltage under load.

---

**Figure-3.3**: Reactive Regulation for 12-Pulse Rectifier using Reactance Factors
3.11.4 12-Pulse Double-Way Rectifiers without Interphase Transformers

12-pulse double-way rectifiers without interphase transformers also exhibit five modes of operation between no load and short circuit.

The direct voltage due to commutating reactance $E_x$ for a 12-pulse double-way rectifier with a rectifier transformer $K_s$ of zero is the same as $E_x$ for the six-pulse rectifier noted in 3.10.2 above for the same reactance factor range (from zero to 1.414).

For values of $F_x$ greater than 0.6214, $E_x$ may be calculated from the various equations in Witzke, Kesser and Dillard [B9]. Alternatively, the corresponding value of $E_d / E_{do}$ may be obtained from Figure 4 above.

If 12-pulse double way rectifiers are used without interphase transformers, it is highly recommended that loosely coupled rectifier transformers be used to obtain the characteristics of rectifier circuit configuration 31. A loosely coupled rectifier transformer produces less eddycurrent winding loss in the windings when an interphase transformer is not used. The impedance of the loosely coupled transformer secondary windings performs a function similar to an interphase transformer. In either case, the additional losses and heating associated with the removal of the IPT shall be accounted for in design and testing.
3.11.5 Effect of Harmonics in Line Voltage
The presence of harmonics in the alternating input voltage of a rectifier unit may affect the direct output voltage. The output voltage of a rectifier is determined by the average voltage applied to an anode during its conducting period; therefore, the effect of a harmonic component of the voltage will depend upon the magnitude, order, and phase position of the harmonic component. In large installations having phase-shifting transformers connected between the alternating current line and the rectifier units, the output voltages of the units may differ because of the different phase relations between the fundamental and harmonic components in the various units.

The effect of harmonics in the alternating-current line voltage arising from the voltage drop in the line reactance with a rectifier unit operating alone may be determined by direct calculation. The effect of harmonics arising from other rectifiers, capacitors, or other sources external to the rectifier can be determined from tests on the installation, or by detailed harmonic load flow simulations.

3.12.0 Power Factor

3.12.1 Value of Power Factor
The power factor of a rectifier unit is less than unity for three reasons:

Distortion of the current wave due to the inherent action of the rectifier. This represents harmonic components in the alternating line current, which do not add to the active power but add to the volt-amperes. The effect of distortion decreases as the number of phases is increased.

Displacement of the fundamental component of the alternating line current with respect to the voltage, due to the reactance of the rectifier transformer.

The effect of transformer exciting current. The power factor is the ratio of kilowatts to kVA measured at the alternating line terminals of the rectifier transformer. It may also be expressed as the ratio of the in-phase or watt component to the rms value of the alternating-current line current. The watt component of the line current is sinusoidal, on the assumption that the alternating line voltage is sinusoidal.

The power factor for a specific load current can be determined by calculation based upon the measured characteristics of the transformer equipment and associated reactors by the method outlined below. Refer to IEEE Std. 519 for additional information.

By the analysis of its theoretical wave shape, the alternating line current can be resolved into its components as follows:

\[ I_L = \text{alternating line current (rms value)} \]
\[ I_{1p} = \text{fundamental watt component of } I_L \]
\[ I_{1q} = \text{fundamental reactive component of } I_L \]
\[ I_H = \sqrt{I_L^2 - I_{1p}^2 - I_{1q}^2} = \text{total harmonic component of } I_L \]
The magnitude of these components will vary with rectifier load and transformer commutating reactance. If the transformer exciting current $I_e$ is assumed to be wholly reactive, with no harmonic components, the power factor is given by:

$$\text{Power Factor (total)} = \frac{I_{1P}}{\sqrt{I_{L}^2 - I_{Lq}^2 + (I_{Lq} + I_e)^2}}$$

The errors resulting from neglecting the watt component and harmonic components of the exciting current are negligible in practical cases.

### 3.12.2 Determination of Displacement Power Factor

Displacement power factor is the ratio of kilowatts to kVA of fundamental frequency at the alternating-current line terminals of the rectifier transformer. The instrumentation commonly employed for determination of power factor is not responsive to the harmonic components of the line current to the rectifier unit, assuming sinusoidal line voltage, and will measure the displacement power factor. The displacement power factor is calculated by the same procedure, harmonic component $I_H$ is neglected.

$$\text{Displacement Power Factor} = \frac{I_{1P}}{\sqrt{I_{1P}^2 + (I_{Lq} + I_e)^2}}$$

The theoretical value of displacement power factor, as a function of the per unit direct voltage drop caused by the commutating reactance, neglecting transformer magnetizing current, is:

$$\cos(\phi 1') = (Edo - Ex)/ Edo$$

### 3.13.0 Tolerances and Unbalance Criteria

#### 3.13.1 Voltage Regulation

The voltage regulation in the rated overload range shall be within the purchaser’s specified output voltage versus rectifier load current tolerance curve, or within the specified ±percent tolerance if a tolerance curve is not specified, when the rectifier transformer is set on the rated voltage tap and is connected to an alternating-current system having the specified sinusoidal voltage and impedance. If no tolerance is specified, the voltage regulation in the overload range shall be ±10 percent of the specified value when the rectifier transformer is set on the rated voltage tap and is connected to an alternating-current system having the specified sinusoidal voltage and impedance.
3.13.2 Rated Output Voltage
The output direct voltage (inherent), as determined by calculation (see 3.11.3), shall not differ from the rated value by more than one percent or two volts, whichever is higher, when the rectifier transformer is set on the rated voltage tap and is connected to an alternating-current system having the specified sinusoidal voltage and impedance (inherent) for which compensation is provided.

3.13.3 Displacement Power Factor
In an uncontrolled rectifier, the displacement power factor \( \cos(\phi_1) \) is determined by the voltage regulation. If a power factor is specified which is in conflict with power factor determined by the voltage regulation specification, the voltage regulation specification shall take precedence, and the power factor defined by the regulation shall be substituted for that specified.

3.13.4 Current Unbalance within Rectifier Units
The supplier of rectifier units shall coordinate rectifier, rectifier transformer, interconnecting circuits and interphase transformer (where applicable) designs to provide equipment that meets performance requirements for current unbalance. Unit equipment shall be designed such that phase and bridge current unbalance does not exceed ±10 percent between 50 and 150 percent rated current with input power quality parameters in compliance with IEEE Std. 519; this shall be achieved without the need for balancing reactors.

3.13.5 Parallel Operation of Rectifier Units.
A rectifier unit shall be considered to be in satisfactory parallel operation with other rectifier units if its output direct current does not differ from its proportionate share of the total current by more than ±10 percent when operating from 50 percent to 150 percent of rated load at rated voltage with input power quality parameters in compliance with IEEE Std. 519. The proportionate share of current for a unit is the total current multiplied by the ratio of the rated current of the unit to the sum of the rated currents of all the units operating in parallel. This does not imply that the rectifier will be permitted to operate beyond its nameplate ratings.

The supplier of rectifier units intended for parallel operation shall prepare detailed calculations demonstrating satisfactory parallel operation for submission with equipment shop drawings. If certain operating conditions shall prevail for successful parallel operation, these conditions shall be stated by the supplier.

3.13.6 Diode Current Unbalance
Parallel diodes shall be designed to remain within specified performance limits under all operating conditions, including short circuit conditions, with the specified number of diodes removed (if any). No diode shall carry more than 120% of its proportionate share of the rectifier section current under all operating conditions.
3.14.0 Auxiliaries

3.14.1 Rectifier Auxiliaries
Limits of temperature rise and allowable variation from rated voltage and frequency for auxiliary apparatus such as motors, transformers, and control and indication devices shall be governed by existing North American Standards for such equipment, where applicable.

4.0 THREE PHASE CONTROLLED RECTIFIER

4.1 Definition
Controlled rectifiers are line commutated ac to dc power converters which are used to convert a fixed voltage, fixed frequency ac power supply into variable dc output voltage.

![Controlled Rectifier Diagram](image)

Figure-4.1: Controlled Rectifier
Type of input: Fixed voltage, fixed frequency ac power supply.
Type of output: Variable dc output voltage

The input supply fed to a controlled rectifier is ac supply at a fixed rms voltage and at a fixed frequency. We can obtain variable dc output voltage by using controlled rectifiers. By employing phase controlled thyristors in the controlled rectifier circuits we can obtain variable dc output voltage and variable dc (average) output current by varying the trigger angle (phase angle) at which the thyristors are triggered. We obtain a uni-directional and pulsating load current waveform, which has a specific average value.

The thyristors are forward biased during the positive half cycle of input supply and can be turned ON by applying suitable gate trigger pulses at the thyristor gate leads. The thyristor current and the load current begin to flow once the thyristors are triggered (turned ON) say at \( \omega t = \alpha \). The load current flows when the thyristors conduct from \( \omega t = \alpha \) to \( \beta \). The output voltage across the load follows the input supply voltage through the conducting thyristor. At \( \omega t = \beta \), when the load current falls to zero, the thyristors turn off due to AC line (natural) commutation.
In some bridge controlled rectifier circuits the conducting thyristor turns off, when the other thyristor is (other group of thyristors are) turned ON.

The thyristor remains reverse biased during the negative half cycle of input supply. The type of commutation used in controlled rectifier circuits is referred to AC line commutation or Natural commutation or AC phase commutation.

When the input ac supply voltage reverses and becomes negative during the negative half cycle, the thyristor becomes reverse biased and hence turns off. There are several types of power converters which use ac line commutation. These are referred to as line commutated converters.

Three-phase controlled rectifiers have a wide range of applications, from small rectifiers to large high voltage direct current (HVDC) transmission systems. They are used for electrochemical processes, many kinds of motor drives, traction equipment, controlled power supplies and many other applications. From the point of view of the commutation process, they can be classified into two important categories: line-commutated controlled rectifiers (thyristor rectifiers) and force-commutated pulse width modulated (PWM) rectifiers.

4.1.0 Line-commutated Controlled Rectifiers

4.1.1 Three-phase Half-wave Rectifier

Figure 4.2: shows the three-phase half-wave rectifier topology. To control the load voltage, the half-wave rectifier uses three common-cathode thyristor arrangement. In this figure, the power supply and the transformer are assumed ideal. The thyristor will conduct (ON state), when the anode-to-cathode voltage \( v_{AK} \) is positive and a firing current pulse \( i_G \) is applied to the gate terminal. Delaying the firing pulse by an angle \( \alpha \) controls the load voltage. As shown in Fig. 4.3, the firing angle \( \alpha \) is measured from the crossing point between the phase supply voltages. At that point, the anode-to-cathode thyristor voltage \( v_{AK} \) begins to be positive. Figure 4.4 shows that the possible range for gating delay is between \( \alpha = 0^\circ \) and \( \alpha = 180^\circ \), but because of commutation problems in actual situations, the maximum firing angle is limited to around \( 160^\circ \). As shown in Fig. 4.5, when the load is resistive, current \( i_d \) has the same waveform of the load voltage. As the load becomes more and more inductive, the current flattens and finally becomes constant. The thyristor goes to the non-conducting condition (OFF state) when the following thyristor is switched ON, or the current, tries to reach a negative value.
With the help of Figure 4.2, the load average voltage can be evaluated, and is given by:

\[
V_D = \frac{V_{MAX}}{2} \int_0^{\frac{\pi}{3}} \cos(\omega t) \cdot d(\omega t) = V_{MAX} \frac{3}{\pi} \cdot \cos(\alpha) = 1.17 \cdot V_{rmsf-N} \cdot \cos(\alpha)
\]

................................. (4.1)

Where \( V_{MAX} \) is the secondary phase-to-neutral peak voltage, \( V_{rmsf-N} \) its root mean square \((rms)\) value and \( \omega \) is the angular frequency of the main power supply. It can be seen from Eq. (4.1) that the load average voltage \( V_D \) is modified by changing firing angle \( \alpha \). When \( \alpha < 90^\circ \), \( V_D \) is positive and when \( \alpha > 90^\circ \), the average \( dc \) voltage becomes negative. In such a case, the rectifier begins to work as an inverter and the load needs to be able to generate power reversal by reversing its \( dc \) voltage.

Figure 4.2: Three Phase Half-wave Controlled Rectifier

Figure 4.3: Instantaneous \( dc \) voltage \( v_D \), average \( dc \) voltage \( V_D \), and firing angle \( \alpha \).
Figure-4.4: Possible range for gating delay in angle $\alpha$

Figure-4.5: DC Current waveforms.
The ac currents of the half-wave rectifier are shown in Fig. 4.6. This drawing assumes that the dc current is constant (very large $L_D$). Disregarding commutation overlap each valve conducts during $120^\circ$ per period. The secondary currents (and thyristor currents) present a dc component that is undesirable, and makes this rectifier not useful for high power applications. The primary currents show the same waveform, but with the dc component removed. This very distorted waveform requires an input filter to reduce harmonics contamination.

Figure-4.6: AC current waveforms for the half-wave rectifier.

The current waveforms shown in Fig. 4.6 are useful for designing the power transformer. Starting from:

$$VA_{prim} = 3 \cdot V_{rms (prim)} \cdot f \cdot N \cdot I_{rms (prim)}$$

$$VA_{sec} = 3 \cdot V_{rms (sec)} \cdot f \cdot N \cdot I_{rms (sec)}$$

$$P_D = V_D \cdot I_D$$

(...)

where $VA_{prim}$ and $VA_{sec}$ are the ratings of the transformer for the primary and secondary side respectively. Here $P_D$ is the power transferred to the dc side. The maximum power transfer is with $\alpha = 0^\circ$ (or $\alpha = 180^\circ$). Then, to establish a relation between ac and dc voltages, Eq. (4.1) for $\alpha = 0^\circ$ is required:
where \( a \) is the secondary to primary turn relation of the transformer. On the other hand, a relation between the currents is also possible to obtain. With the help of Fig-4.6.

\[
I_{sec}^{\text{rms}} = \frac{I_D}{\sqrt{3}} \text{ .............................................................. (4.5)}
\]

Combining Eqs. (4.2) to (4.6), it yields:

\[
\begin{align*}
V_{A\text{,prin}} &= 1.21 \cdot P_D \\
V_{A\text{,sec}} &= 1.48 \cdot P_D \quad \text{ .............................................................. (4.7)}
\end{align*}
\]

The meaning of Equation (4.7) shows that the power transformer has to be oversized 21% at the primary side, and 48% at the secondary side. Then, a special transformer has to be built for this rectifier. In terms of average VA, the transformer needs to be 35% larger than the rating of the \textit{dc} load. The larger rating of the secondary with respect to primary is because the secondary carries a \textit{dc} component inside the windings. Furthermore, the transformer is oversized because the circulation of current harmonics does not generate active power. Core saturation, due to the \textit{dc} components inside the secondary windings, also needs to be taken in account for iron oversizing, because the circulation of current harmonics does not generate active power. Core saturation, due to the \textit{dc} components inside the secondary windings, also needs to be taken in account for iron oversizing.
4.1.2 Six-pulse or Double Star Rectifier

The thyristor side windings of the transformer shown in Fig. 4.7 form a six-phase system, resulting in a six-pulse starpoint (midpoint connection). Disregarding commutation overlap, each valve conducts only during 60° per period. The direct voltage is higher than that from the half-wave rectifier and its average value is given by:

\[
V_D = \frac{V_{MAX}}{\pi} \frac{\pi \cdot \alpha}{6} \int_{-\alpha}^{\alpha} \cos \omega t \cdot d(\omega t) \\
= V_{MAX} \frac{\sin \frac{\pi}{6}}{\pi} \cdot \cos \alpha \approx 1.35 \cdot V_{\text{rms}} \cdot \cos \alpha
\]

\[\text{..........................}(4.8)\]

The dc voltage ripple is also smaller than the one generated by the half-wave rectifier, due to the absence of the third harmonic with its inherently high amplitude. The smoothing reactor \(L_D\) is also considerably smaller than the one needed for a three-pulse (half-wave) rectifier.

Figure 4.7: Six-Pulse Rectifier

The ac currents of the six-pulse rectifier are shown in Fig. 4.8. The currents in the secondary windings present a dc component, but the magnetic flux is compensated by the double star. As can be observed, only one valve is fired at a time and then this connection in no way corresponds to a parallel connection. The currents inside the delta show a symmetrical waveform with 60° conduction. Finally, due to the particular transformer connection shown in Fig. 4.7, the source currents also show a symmetrical waveform, but with 120° conduction.
Evaluation of the the rating of the transformer is done in similar fashion to the way the half-wave rectifier is evaluated:

\[ VA_{\text{prim}} = 1.28 \cdot P_D \]
\[ VA_{\text{sec}} = 1.81 \cdot P_D \] \hspace{1cm} (4.9)

Thus the transformer must be oversized 28\% at the primary side and 81\% at the secondary side. In terms of size it has an average apparent power of 1.55 times the power \( P_D \) (55\% oversized). Because of the short conducting period of the valves, the transformer is not particularly well utilized.
4.1.3 Double Star Rectifier with Interphase Connection

This topology works as two half-wave rectifiers in parallel, and is very useful when high \( dc \) current is required. An optimal way to reach both good balance and elimination of harmonics is through the connection shown in Fig. 4.9. The two rectifiers are shifted by 180°, and their secondary neutrals are connected through a middle-point autotransformer called “interphase transformer.” The interphase transformer is connected between the two secondary neutrals and the middle point at the load return. In this way, both groups operate in parallel. Half the direct current flows in each half of the interphase transformer, and then its iron core does not become saturated. The potential of each neutral can oscillate independently, generating an almost triangular voltage waveform \( (v_T) \) in the interphase transformer, as shown in Fig. 4.10. As this converter work like two half-wave rectifiers connected in parallel, the load average voltage is the same as in Eq. (4.1):

\[
V_D' \approx 1.17 \cdot V_{f-N}^{rms} \cdot \cos \alpha \tag{4.10}
\]

Where \( V_{f-N}^{rms} \) is the phase-to-neutral \( rms \) voltage at the valve side of the transformer (secondary).

![Diagram of Double Star Rectifier with Interphase Transformer](image)

Figure 4.9: Double star rectifier with interphase transformer

Fig. 4.10 also shows the two half-wave rectifier voltages, related to their respective neutrals. Voltage \( v_{D1} \) represents the potential between the common cathode connection and the neutral N1. The voltage \( v_{D2} \) is between the common cathode connection and N2. It can be seen that the two instantaneous voltages are shifted, which gives as a result, a voltage \( v_D \) that is smoother than \( v_{D1} \) and \( v_{D2} \).
Figure 4.10: Operation of the interphase connection for $\alpha = 0^\circ$

Figure 4.11: shows how $v_D$, $v_{D1}$, $v_{D2}$, and $v_T$ change when the firing angle changes from $\alpha = 0^\circ$ to $180^\circ$.

Figure 4.11: Firing angle variation from $\alpha = 0^\circ$ to $180^\circ$
The transformer rating in this case is:

\[
V_{A_{\text{per}}} = 1.05 \cdot P_D \\
V_{A_{\text{sec}}} = 1.48 \cdot P_D
\]  

(4.11)

And the average rating power will be 1.26 \( P_D \), which is better than the previous rectifiers (1.35 for the half-wave rectifier and 1.55 for the six-pulse rectifier). Thus the transformer is well utilized.

Figure 4.12: shows AC current waveforms for a rectifier with interphase transformer.

4.1.4 Three-phase Full-wave Rectifier or Graetz Bridge

Parallel connection via interphase transformers permits the implementation of rectifiers for high current applications. Series connection for high voltage is also possible, as shown in the full-wave rectifier of Figure 4.13. With this arrangement, it can be seen that the three common cathode valves generate a positive voltage with respect to the neutral, and the three common anode valves produce a negative voltage. The result is a dc voltage, twice the value of the half-wave rectifier. Each half of the bridge is a three-pulse converter group. This bridge connection is a two-way connection and alternating currents flow in the valve-side transformer windings during both half
periods, avoiding $dc$ components into the windings, and saturation in the transformer magnetic core. These characteristics make the so-called Graetz bridge the most widely used linecommutated thyristor rectifier. The configuration does not need any special transformer and works as a six-pulse rectifier. The series characteristic of this rectifier produces a $dc$ voltage twice the value of the half-wave rectifier. The load average voltage is given by:

$$V_D = \frac{2 \cdot V_{MAX} \cdot \frac{\pi}{3} \sin \frac{\pi}{3} \cdot \cos \alpha}{\frac{\pi}{3} \cdot \cos \alpha} = 2 \cdot V_{MAX} \cdot \frac{\sin \frac{\pi}{3}}{\frac{\pi}{3} \cdot \cos \alpha} \approx 2.34 \cdot V_{f-N}^{rms} \cdot \cos \alpha$$

\hspace{1cm} ......................(4.12)

$$V_D = \frac{3 \cdot \sqrt{2} \cdot V_{f-sec}^{rms}}{\pi} \cdot \cos \alpha \approx 1.35 \cdot V_{f-sec}^{rms} \cdot \cos \alpha$$

\hspace{1cm} ........................................(4.13)

Where $V_{MAX}$ is the peak phase-to-neutral voltage at the secondary transformer terminals, $V_{f-N}^{rms}$ its rms value, and $V_{f-sec}^{rms}$ the rms phase-to-phase secondary voltage, at the valve terminals of the rectifier.

Figure-4.13: Three-phase full-wave rectifier or Graetz Bridge
The figure-4.14 shows the voltages of each half wave bridge of this topology, \( v_{D^{pos}} \) and \( v_{D^{neg}} \), the total instantaneous dc voltage \( v_D \), and the anode-to-cathode voltage \( v_{AK} \) in one of the bridge thyristors. The maximum value of \( v_{AK} \) is \( \sqrt{3} \cdot V_{MAX} \), which is the same as of the half-wave converter, and the interphase transformer rectifier. The double star rectifier presents a maximum anode-to-cathode voltage of 2 times \( V_{MAX} \). The figure-4.15 shows the currents of the rectifier, which assumes that \( L_D \) is large enough to keep the dc current smooth. The example is for the same \( \Delta Y \) transformer connection shown in the topology of figure-4.13. It can be noted that the secondary currents do not carry any dc component, avoiding the overdesign of windings, and transformer saturation. These two figures have been drawn for a firing angle \( \alpha \) of approximately 30°. The perfect symmetry of the currents in all windings and lines is one of the reasons why this rectifier is the most popular in its type. The transformer rating in this case is:

\[
\begin{align*}
V_{A^{\text{prim}}} &= 1.05 \cdot P_D \\
V_{A^{\text{sec}}} &= 1.05 \cdot P_D
\end{align*}
\] (4.14)

As it can be noted, the transformer only needs to be oversized 5\%, and both, primary and secondary windings have the same rating. Again, this value can be compared with the previous rectifier transformers: \( 1.35P_D \) for the half wave rectifier, \( 1.55P_D \) for the six-pulse rectifier, and \( 1.26P_D \) for the interphase transformer rectifier. The Graetz Bridge makes an excellent use of the power transformer.
Figure-4.14: Voltage waveforms for the Graetz Bridge
4.1.5 Half controlled bridge converter
The fully controlled three-phase bridge converter shown in figure-4.13 has six thyristors. As explained above, this circuit operates as a rectifier when each thyristor has a firing angle, $\alpha$, which is less than 90 degrees, and functions as an inverter for $\alpha$ greater than 90 degrees. If inverter operation is not required, the circuit may be simplified by replacing three controlled rectifiers with power diodes, as in figure 4.16 (a). This simplification is economically attractive because diodes are considerably less expensive than thyristors, and they do not require firing angle control electronics.
The half controlled bridge, or “Semiconverter”, is analyzed by considering it as a phasecontrolled half-wave circuit in series with an uncontrolled half wave rectifier. The average $dc$ voltage is given by the following equation:

$$V_D = \frac{3 \cdot \sqrt{2} \cdot V_{\text{sec}}}{2\pi} (1 + \cos \alpha)$$

(4.15)

Then, the average voltage $V_D$ never reaches negative values. The output voltage waveforms of half-controlled bridge are similar to those of a fully controlled bridge with a free-wheeling diode. The advantage of the free-wheeling diode connection, shown in figure 4.16 (b) is that there is always a path for the $dc$ current, independent of the status of the $ac$ line and of the converter. This can be important if the load is inductive-resistive with a large time constant, and there is an interruption in one or more of the line phases. In such a case, the load current could commutate to the free-wheeling diode.

![Diagram of bridge converter circuits](image)

Figure-4.16: One-quadrant bridge converter circuits

a) half-controlled bridge; b) free-wheeling diode bridge

### 4.1.6 Commutation

The description of the converters in the previous sections was based upon assumption that the commutation was instantaneous. In practice this is not possible, because the transfer of current between two consecutive valves in a commutation group takes a finite time. This time, called *overlap time*, depends on the phase-to-phase voltage between the valves participating in the commutation process, and the line inductance $L_S$, between the converter and power supply. During the overlap time, two valves conduct, and the phase-to-phase voltage drops entirely on the inductances $L_S$. Assuming the $dc$ current $I_D$ to be smooth, and with the help of figure-4.17, the following relation is deducted:
where $i_{sc}$ is the current in the valve being fired during the commutation process (thyristor T2 in figure-4.17. This current can be evaluated, and it yields:

\[
i_{sc} = -\frac{\sqrt{2}}{2L_s} \cdot V_{f-f} \cdot \frac{\cos \omega t}{\omega} + C
\]

................................. (4.17)

The constant “C” is evaluated through initial conditions at the instant when T2 is ignited. In terms of angle, when $\omega t = \alpha$:

\[
\text{when } \omega t = \alpha, \quad i_{sc} = 0 \quad \therefore C = \frac{V_{f-f}}{\sqrt{2} \cdot \omega L_s} \cos \alpha
\]

................................. (4.18)
Replacing (4.18) in (4.17):

$$i_{sc} = \frac{V_{f-f}}{\sqrt{2} \cdot \omega L_s} \cdot (\cos \alpha - \cos \omega t)$$

\[ \text{(4.19)} \]

Before commutation, the current $I_D$ was carried by thyristor T1 (see figure-4.17). During the commutation time, the load current $I_D$ remains constant, $i_{sc}$ returns through T1, and T1 is automatically switched-off when the current $i_{sc}$ reaches the value of $I_D$. This happens because thyristors cannot conduct in reverse direction. At this moment, the overlap time lasts, and the current $I_D$ is then conducted by T2. In terms of angle:

when $\omega t = \alpha + \mu$,  $i_{sc} = I_D$

where $\mu$ is defined as the “overlap angle”. Replacing this final condition in (4.19) it yields:

$$I_D = \frac{V_{f-f}^{sec}}{\sqrt{2} \cdot \omega L_s} \cdot [\cos \alpha - \cos(\alpha + \mu)]$$

\[ \text{(4.20)} \]

To avoid confusion in a real analysis, it has to be remembered that $V_{f-f}$ corresponds to the secondary voltage in case of transformer utilization. For this reason in equation (4.20) the word “sec” has been added to the phase-to-phase voltage.

During the commutation, two valves conduct at a time, which means that there is an instantaneous short circuit between the two voltages participating in the process. As the inductances of each phase are the same, the current $i_{sc}$ produces the same voltage drop in each $L_S$, but with opposite sign because this current flows in reverse direction in each inductance. The phase with the higher instantaneous voltage suffers a voltage drop $-\Delta v$, and the phase with the lower voltage suffers a voltage increase $+\Delta v$. This situation affects the $dc$ voltage $V_C$, reducing its value an amount $\Delta V_{med}$. The figure-4.18 shows the meanings of $\Delta v$, $\Delta V_{med}$, $\mu$, and $i_{sc}$. 
Figure-4.18: Effect of the overlap angle on the voltages and currents

The area $\Delta V_{med}$ showed in figure 4.18, represents the loss of voltage that affects the average voltage $V_C$, and can be evaluated through the integration of $\Delta v$ during the overlap angle $\mu$. The voltage drop $\Delta v$ can be expressed as:

$$\Delta v = \left( \frac{V_A - V_B}{2} \right) = \frac{\sqrt{2} \cdot V_{res} \sin \omega t}{2}$$ ...............(4.21)

Integrating eq. (4.21) into the corresponding period (60°) and interval ($\mu$), at the instant when the commutation begins ($\alpha$):

$$\Delta V_{med} = \frac{3}{\pi} \cdot \frac{1}{2} \int_{\alpha}^{\alpha + \mu} \sqrt{2} \cdot V_{res} \sin \omega t \cdot d\omega t$$ ...............(4.22)
\[ \Delta V_{\text{med}} = \frac{3 \cdot V_{\text{sec}}^{\text{f-f}}}{\pi \cdot \sqrt{2}} [\cos \alpha - \cos(\alpha + \mu)] \] .............................. (4.23)

Subtracting \( \Delta V_{\text{med}} \) in eq. (4.13):

\[ V_D = \frac{3 \cdot \sqrt{2} \cdot V_{\text{sec}}^{\text{f-f}}}{\pi} \cos \alpha - \Delta V_{\text{med}} \] .............................. (4.24)

\[ V_D = \frac{3 \cdot \sqrt{2} \cdot V_{\text{sec}}^{\text{f-f}}}{2\pi} [\cos \alpha + \cos(\alpha + \mu)] \] .............................. (4.25)

Or,

\[ V_D = \frac{3 \cdot \sqrt{2} \cdot V_{\text{sec}}^{\text{f-f}}}{\pi} \left[ \cos \left( \alpha + \frac{\mu}{2} \right) \cos \frac{\mu}{2} \right] \] .............................. (4.26)

(4.20) and (4.25) can be written as a function of the primary winding of the transformer, if any.

\[ I_D = \frac{a \cdot V_{\text{prim}}^{\text{f-f}}}{\sqrt{2} \cdot \omega L_S} [\cos \alpha - \cos(\alpha + \mu)] \] .............................. (4.27)

\[ V_D = \frac{3 \cdot \sqrt{2} \cdot a \cdot V_{\text{prim}}^{\text{f-f}}}{2\pi} [\cos \alpha + \cos(\alpha + \mu)] \] .............................. (4.28)

Where \( a=V_{\text{sec}}^{\text{f-f}}/V_{\text{prim}}^{\text{f-f}} \). With (12.27) and (12.28) one gets:

\[ V_D = \frac{3 \cdot \sqrt{2}}{\pi} \cdot a \cdot V_{\text{prim}}^{\text{f-f}} \cos \alpha - \frac{3 I_{\text{f-f}} \omega L_S}{\pi} \] .............................. (4.29)
Equation (4.19) allows making a very simple equivalent circuit of the converter, which is shown in figure 12.18. It is important to note that the equivalent resistance of this circuit is not real, because it does not dissipate power.

![Equivalent Circuit for converter](image)

Figure-4.19: Equivalent Circuit for converter

From the equivalent circuit, regulation curves for the rectifier, under different firing angles are shown in figure 12.19. It should be noted that these curves only correspond to an ideal situation, but helps in the understanding of the effect of the voltage drop $\Delta v$ on the $dc$ voltage.

![DC Voltage regulation curves for rectifier operation](image)

Figure-4.20: DC Voltage regulation curves for rectifier operation
4.1.7 Power factor
The displacement factor of the fundamental current, obtained from Figure-4.15 is:

$$\cos \phi_1 = \cos \alpha$$  

(4.30)

In the case of non-sinusoidal current, the active power delivered per phase by the sinusoidal supply is

$$P = \frac{1}{T} \int_0^T v_a(t) i_a(t) dt = V_{a_{\text{rms}}} I_{a1_{\text{rms}}} \cos \phi_1$$

(4.31)

where $V_{a_{\text{rms}}}$ is the $\text{rms}$ value of the voltage $v_a$, and $I_{a1_{\text{rms}}}$ the $\text{rms}$ value of $i_{a1}$ (fundamental component of $i_a$). Analog relations can be obtained for $v_b$ and $v_c$.

The apparent power per phase is given by:

$$S = V_{a_{\text{rms}}} I_{a_{\text{rms}}}$$

(4.32)

The power factor is defined by:

$$PF = \frac{P}{S}$$

(4.33)
Replacing equations (4.30), 94.31) and (4.32) in equation (4.33), the power factor can be expressed as follows:

\[ PF = \frac{I_{\text{rms}}}{I_{a \text{rms}}} \cos \alpha \]

.................................................................(4.34)

This equation shows clearly that due to the non-sinusoidal waveform of the currents, the power factor of the rectifier is negatively affected both by the firing angle \( \alpha \) and by the distortion of the input current. In effect, an increase in the distortion of the current produces an increase in the value of \( I_{a \text{rms}} \) in equation (12.34), which deteriorates the power factor.

**4.1.8 Harmonic distortion**

The currents of the line-commutated rectifiers are far from being sinusoidal. For example, the currents generated from the Graetz rectifier (see figure 4.15(b)) have the following harmonic content:

\[ i_a = \frac{2\sqrt{3}}{\pi} I_D (\cos \omega t - \frac{1}{5} \cos 5 \omega t + \frac{1}{7} \cos 7 \omega t - \frac{1}{11} \cos 11 \omega t + ...) \]

.................................................................(4.35)

Some characteristics of the currents, obtained from equation (4.35) are: i) the absence of triple harmonics; ii) the presence of harmonics of order \( 6k \pm 1 \) for integer values of \( k \); iii) those harmonics of orders \( 6k + 1 \) are of positive sequence, and those of orders \( 6k - 1 \) are of negative sequence; v) the \( \text{rms} \) magnitude of the fundamental frequency is:

\[ I_1 = \frac{\sqrt{6}}{\pi} I_D \]

.................................................................(4.36)

The \( \text{rms} \) magnitude of the \( n^{th} \) harmonic is:

\[ I_n = \frac{I_1}{n} \]

.................................................................(4.37)
If either, the primary or the secondary three-phase windings of the rectifier transformer are connected in delta, the ac side current waveforms consist of the instantaneous differences between two rectangular secondary currents 120° apart as showed in figure-4.15 (e). The resulting Fourier series for the current in phase “a” on the primary side is:

\[
i_a = \frac{2\sqrt{3}}{\pi} I_D (\cos \omega t + \frac{1}{5} \cos 5\omega t - \frac{1}{7} \cos 7\omega t - \frac{1}{11} \cos 11\omega t + ...) \tag{4.38}
\]

This series only differs from that of a star connected transformer by the sequence of rotation of harmonic orders 6k ± 1 for odd values of k, i.e. the fifth, seventh, 17th, 19th, etc.

### 4.1.9 Special configurations for harmonic reduction

A common solution for harmonic reduction is through the connection of passive filters, which are tuned to trap a particular harmonic frequency. A typical configuration is shown in figure 4.22.

![Figure-4.22: Typical passive filter for one phase](image)

However, harmonics can also be eliminated using special configurations of converters. For example, twelve-pulse configuration consists of two sets of converters connected as shown in figure-4.23. The resultant ac current is given by the sum of the two Fourier series of the star connection (equation 4.35) and delta connection transformers (equation 4.38):

\[
i_a = 2 \left( \frac{2\sqrt{3}}{\pi} \right) I_D (\cos \omega t - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t - \frac{1}{23} \cos 23\omega t + ...) \tag{4.39}
\]

The series only contains harmonics of order 12k ± 1. The harmonic currents of orders 6k ± 1 (with k odd), i.e. 5th, 7th, 17th, 19th, etc., circulate between the two converter transformers but do not penetrate the ac network.
The resulting line current for the twelve-pulse rectifier is shown in figure-4.24, which is closer to a sinusoidal waveform than previous line currents. The instantaneous $dc$ voltage also results smoother with this connection.

Figure-4.24: Line Current for the Twelve-Pulse Rectifier
Higher pulse configuration using the same principle is also possible. The twelve-pulse was obtained with a 30° phase-shift between the two secondary transformers. The addition of further appropriately shifted transformers in parallel provides the basis for increasing pulse configurations. For instance, 24-pulse operation is achieved by means of four transformers with 15° phase-shift, and 48-pulse operation requires eight transformers with 7.5° phase-shift.

Although theoretically possible, pulse numbers above 48 are rarely justified due to the practical levels of distortion found in the supply voltage waveforms. Besides, the converter topology becomes more and more complicated.

An ingenious and very simple way to reach high pulse operation is shown in figure-4.25. This configuration is called *dc* ripple re-injection. It consists of two parallel converters connected to the load through a multi-step reactor. The reactor uses a chain of thyristor-controlled taps, which are connected to symmetrical points of the reactor. By firing the thyristors located at the reactor at the right time, the high-pulse operation is reached. The level of pulse-operation depends on the number of thyristors connected to the reactor. They multiply the basic level of operation of the two converters. The example of figure 38 shows a 48-pulse configuration, obtained by the multiplication of basic 12-pulse operation by 4 reactor thyristors. This technique can also be applied to series connected bridges.

![Figure-4.25: DC ripple reinjection technique for 48-pulse operation](image-url)
Another solution for harmonic reduction is the utilization of active power filters. Active power filters are special Pulse Width Modulated (PWM) converters, able to generate the harmonics the converter requires. The figure-4.26 shows a current controlled shunt active power filter.

![Figure-4.26: Current Controlled shunt active power filter](image)

### 4.1.10 Applications in HVDC power transmission

High Voltage Direct Current (HVDC) power transmission is the more powerful application for line-commutated converters existing today. There are power converters with ratings in excess of 1,000 MW. Series operation of hundreds of valves can be found in some HVDC systems. In high power and long distance applications, these systems become more economic than conventional ac systems. They also have some other advantages compared with ac systems: 1) they can link two ac systems operating unsynchronized or with different nominal frequencies, i.e. 50Hz ↔ 60 Hz; 2) they can help in stability problems related with subsynchronous resonance in long ac lines; 3) they have very good dynamic behavior, and can interrupt short circuits problems very quick; 4) if transmission is by submarine or underground cable, it is not practical to consider ac cable systems exceeding 50 km, but dc cable transmission systems are in service whose length is in hundreds of kilometers and even distances of 600 km or greater have been considered feasible; 5) reversal of power can be controlled electronically by means of the delay firing angles α; 6) some existing overhead ac transmission lines cannot be increased. If upgraded to or overbuilt with dc transmission can substantially increase the power transfer capability on the existing right-of-way.
Some interesting applications of HVDC systems are for interconnections of asynchronous systems. Some continental electric power systems consist of asynchronous networks such as the East-West Texas and Quebec networks in North America, and islands loads such as the Island of Gotland in the Baltic Sea make good use of the HVDC interconnections.

Nearly all HVDC power converters with thyristor valves are assembled in a converter bridge of twelve-pulse configuration, as shown in figure-4.27. Consequently the ac voltages applied to each six-pulse valve group which make up the twelve-pulse valve group have a phase difference of 30 degrees which is utilized to cancel the ac side 5th and 7th harmonic currents and dc side 6th harmonic voltage, thus resulting in a significant saving in harmonic filters.

![Diagram of HVDC Power System](image)

Simplified Unilinear Diagram:

Figure 4.27: Typical HDVC Power System: a)Detailed Circuit and b) Unilinear Diagram
4.1.11 Harmonic standards and recommended practices

In view of the proliferation of the power converter equipment connected to the utility system, various national and international agencies have been considering limits on harmonic current injection to maintain good power quality. As a consequence, various standards and guidelines have been established that specify limits on the magnitudes of harmonic currents and harmonic voltages.

CENELEC (Comité Européen de Normalisation Electrotechnique), IEC (International Electrical Commission), and VDE (West German Standards) specify the limits on the voltages (as a percentage of the nominal voltage) at various harmonics frequencies of the utility frequency, when the equipment-generated harmonic currents are injected into a network whose impedances are specified.

According with IEEE-519 (Institute of Electrical and Electronic Engineers), the table 4.1 lists the limits on the harmonic currents that a user of power electronics equipment and other nonlinear loads is allowed to inject into the utility system. Table 4.2 lists the quality of voltage that the utility can furnish the user.

Table 4.1: Harmonic current limits in percent of fundamental

<table>
<thead>
<tr>
<th>Short circuit current [pu]</th>
<th>$h&lt;1$</th>
<th>$11&lt;h&lt;17$</th>
<th>$17&lt;h&lt;23$</th>
<th>$23&lt;h&lt;35$</th>
<th>$35&lt;h$</th>
<th>THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>4.0</td>
<td>2.0</td>
<td>1.5</td>
<td>0.6</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>20-50</td>
<td>7.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td>50-100</td>
<td>10.0</td>
<td>4.5</td>
<td>4.0</td>
<td>1.5</td>
<td>0.7</td>
<td>12.0</td>
</tr>
<tr>
<td>100-1000</td>
<td>12.0</td>
<td>5.5</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
<td>15.0</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>15.0</td>
<td>7.0</td>
<td>6.0</td>
<td>2.5</td>
<td>1.4</td>
<td>20.0</td>
</tr>
</tbody>
</table>
Table 4.2: Harmonic voltage limits in percent of fundamental

<table>
<thead>
<tr>
<th>Voltage level</th>
<th>2.3-69 kV</th>
<th>69-138 kV</th>
<th>&gt;138 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum for individual harmonic</td>
<td>3.0</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Total Harmonic Distortion (THD)</td>
<td>5.0</td>
<td>2.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

In table 4.1, the values are given at the point of connection of nonlinear loads. The THD is the total harmonic distortion given by equation 12.51, and \( h \) is the number of the harmonic.

\[
THD = \sqrt{\sum_{h=2}^{\infty} I_h^2} / I_1
\]

The total current harmonic distortion allowed in table 4.1 increases with the value of short circuit current.

The total harmonic distortion in the voltage can be calculated in a manner similar to that given by equation 4.40, Table 4.2 specifies the individual harmonics and the THD limits on the voltage that the utility supplies to the user at the connection point.

5.0 MTA-NEW YORK CITY TRANSIT SPECIFICATIONS AND DESIGN GUIDELINE FOR UNCONTROLLED RECTIFIER

5.1.0 MTA New York City Transit Rectifier Specifications

5.1.1 General

1. Rectifiers shall be semiconductor type using silicon cells to provide a fundamental 12-phase ripple. Each individual silicon cell shall be hermetically sealed and mounted on an adequate air-cooled heat sink for necessary heat dissipation. The mating surface of the heat sink shall be machine finished. Each diode shall be provided with a protective fuse and the fuse status for each rectifier leg shall be indicated by two LED indicating lights. A mimic (diode fuse monitoring board) showing the fuse (diode) indicating lights, fuses and diodes for each parallel path in each of the twelve rectifier legs shall be provided in the rectifier cubicle such that it is easily seen from the outside. One indicating light shall indicate a single fuse (diode) failure in the leg and the other, a double fuse (diode) failure in the leg. Provide a current balance between parallel paths in each leg within ten (10) percent of their prorated share. Each individual silicon cell shall have a voltage rating equal to at least 275 percent of the applied peak inverse voltage at no load. The rectifier, with one parallel path in each leg out of service, shall be capable of carrying the rated loads.
2. Rectifier and appurtenances shall withstand 750 volts D.C. that may be impressed on the equipment due to regenerative train braking systems.

3. Rectifier shall be capable of withstanding a bolted short circuit at the output terminals until the fault is cleared, without damage to protective fuses, rectifier elements or any part of the equipment.

4. All current carrying parts of the rectifier shall be copper and shall meet the requirements as per standard.

5. Rectifier shall be designed to function in normally unattended substations. Proper selection of the type and size of individual components and the proper functioning thereof shall be designed as an integral rectifier unit.

5.1.2 Overload Rating.
1. Rectifier shall have a continuous nominal output rating of 3,000-kw or 4,000-kw at 625 volts D.C. After reaching constant temperature at the nominal ratings, the rectifier shall be fully capable, electrically, mechanically and thermally of twice daily delivering an overload rating, power and current cycle in accordance with NEMA R1-9.

5.1.3 Regulation.
1. Based on a constant incoming voltage source and the combined inherent characteristics of equipment and regulating devices the D.C. voltage regulation of the rectifier shall be as indicated in the following table:

Table-5.1: DC Voltage Regulation

<table>
<thead>
<tr>
<th>RECTIFIER SIZE - KW</th>
<th>LOAD (%)</th>
<th>LOAD (AMPS)</th>
<th>D.C. VOLTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000/4000</td>
<td>4.17</td>
<td>200/267</td>
<td>Greater than 656</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Less than 669</td>
</tr>
<tr>
<td>3000/4000</td>
<td>100</td>
<td>4800/6400</td>
<td>625 ± 1%</td>
</tr>
<tr>
<td>3000/4000</td>
<td>200</td>
<td>9600/12800</td>
<td>Greater than 582</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Less than 594</td>
</tr>
<tr>
<td>3000/4000</td>
<td>300</td>
<td>14400/19200</td>
<td>Greater than 538</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Less than 562</td>
</tr>
</tbody>
</table>
5.1.4 Surge Protection.

1. The rectifier equipment shall be adequately protected against lightning strokes and other types of surges which may occur on the system, except a direct strike at the substation.

2. Normal operating condition is the application of 2,600 volt D.C. "spikes" to the rectifier output due to the switching action of the third rail shoes, hence protection shall be provided at voltages exceeding 2,600 volts D.C.

3. The surge protection equipment shall have a "useful life" compatible with the rectifier being protected. Means shall be provided to visually indicate failure of this protective equipment during routine substation inspection.

5.1.5 Rectifier Cooling.

Rectifiers shall be designed for convection cooling at all loads.

5.1.6 Enclosure

1. Each rectifier assembly shall be of the indoor, free standing, metal enclosure type with hinged doors to all compartments, adequately interlocked to prevent exposure of personnel to live parts. Doors shall be provided with adjustable door stops. Enclosure shall have sufficient strength for the support of electrical conduit and buses. The top and sides of the enclosure shall be protected against water leakage. The interior of the enclosure shall be readily accessible for cleaning and maintenance. The control cubicle shall have a minimum of two doors, and the diode cubicle shall have a minimum of four doors. The interior of the control cubicle shall be so arranged as to allow maintenance personnel to turn, stoop or bend down without coming in contact with any equipment which could be made alive. The entry doors shall not be less than 22 inches wide and at least 6 foot 6 inches in height. Adequate illumination with a switch in the control cubicle shall be provided for viewing the interior of the rectifier through observation windows. Openings of the windows shall be sufficiently large to easily view the indication lights.

2. Due to the close proximity of the rectifier to its associated power transformer, there shall be nothing to necessitate observation of, access to or maintenance of the rectifier on the side that faces its transformer. In addition, a nonmetallic protective barrier shall be installed between the rectifier and its associated power transformer to protect personnel in the event that the rectifier compartment should become alive with 600 volts.
3. Isolate the rectifier housing from the supporting floor to eliminate the effect of stray negative return currents. Place stand-off insulators between the underside of the rectifier housing and the supporting floor. Provide eight (8) insulators each 4 inches in diameter and 4 inches high with a 5/8 inch thread. Each insulator shall have a compressive strength rating of 6,000 pounds. The insulators shall be a fiberglass-reinforced thermoset polymer composite system, possessing flame resistance, corrosion resistance, weather ability, and dielectric properties. The material shall meet NEMA criteria for grade GPO-3 and have a dielectric strength of 315kV/inch and arc resistance of 192 seconds. The insulators shall be Glastic or approved equal. Place the insulators at the main supporting members of the floor to provide an equal distribution of the rectifier load.

5.1.7 Rectifier Auxiliary Transformers.
1. Provide an air-cooled, 490 to 120/208 volt, 3 phase, 60 hertz rectifier auxiliary power transformer to furnish power for control devices and auxiliaries. The KVA of this transformer shall be as indicated on the Contract Drawings.

2. The connection between the auxiliary transformers and the auxiliary switchgear shall be with four (4) single conductor cables in conduit. The size of cables shall be as indicated on the Contract Drawings.

5.1.8 Interphase Reactance
When required by the circuit used, furnish and install a suitable interphase reactor and mount it in the rectifier cubicle. Noise level of the rectifier with the interphase reactor shall not exceed the noise levels. Mount the reactor on the floor on noise reducing pads.

5.2.0 EXECUTION.

5.2.1 External Connections.
a. Connections from the low voltage terminals of each rectifier power transformer to the associated rectifier and from each rectifier to the associated machine breaker and negative bus, except as specified below, shall be made with copper bar, copper fittings, approved bolted connections and expansion connectors encased in suitable ventilated bus duct. Insulate ventilated bus duct housing at the connection to the power transformer to prevent the transfer of stray negative currents. To avoid delays in scheduling, the bus work must either be fabricated on site or manufactured ahead of time by an outside plant, omitting only small sections of bus, such lengths of which may be adjusted and delivered after the equipment is in place. Such bar shall be assembled, spaced, insulated and supported at the substation to conform to the on-site routing requirements. The A.C. input terminals of the rectifier shall line up in phase and spacing with the low voltage terminals of the transformers.
5.2.2 Tests

a. Rectifier tests, unless otherwise herein specified, shall be made in accordance with ANSI Test Code C34.2. Complete load-cycle test shall be conducted at the factory. Tests shall be conducted at reduced voltage sufficient to attain the load current ratings specified in Paragraph 5.1.2. A surge test shall be made to test the effectiveness of the surge protection equipment. In this test an impulse voltage of 75 KV shall be applied to a simulated system from a source with a surge impedance comparable to that of the actual circuit. Low-tension auxiliary power transformer tests, unless otherwise herein specified, shall be made in accordance with ANSI Test Code C57.12.90. A complete set of recent tests shall be required on one rectifier and one low-tension auxiliary transformer, and standard factory tests on the other rectifiers and transformers, but, in lieu of a complete set of tests, notarized, certified test data for a complete set of tests on a rectifier and a transformer of the same design and rating will be accepted.

b. Under the supervision and direction of the manufacturer of the rectifier apparatus, perform such functions as are required to conduct a short-circuit test on the rectifier assembly after installation. Test procedures and major equipment shall be furnished by the manufacturer of the rectifier apparatus. Test equipment shall include shunts, calibrated meters, recording oscillographs, shorting devices and all other associated devices required for the test. Furnish all necessary materials and labor for connecting the test equipment and performing the tests. The manufacturer shall be responsible for its performance. Manufacturers’ representatives shall be permitted access to the installation prior to testing to verify that the installation is proper and in accordance with applicable installation instructions.

c. The basic intent of the field short-circuit test is to:

1. Check interrupting adequacy of the D.C. switchgear with utility system capacity and rated voltage.

2. Verify and coordinate the operability of the primary A.C. breaker, D.C. feeder breaker and the individual diode current-limiting fuses utilized in silicon rectifier protection, ground protection and elimination of negative drain currents.

3. Check proper installation of all interconnected apparatus.

4. The field short-circuit test shall consist of the application of a bolted fault at the feeder breaker side terminals before the disconnect switch (open position) and on the DC positive bus before the DC feeder circuit breakers. Both tests shall be performed on one feeder breaker with one rectifier and all other feeder breakers and disconnect switches kept open.

5. Submit and receive approval of the test reports before delivery of or payment for the rectifier.
5.2.3 Efficiency.
The efficiency of the rectifier, including power required for auxiliaries, shall be not less than the following:

<table>
<thead>
<tr>
<th>Percent Rated D.C. Current</th>
<th>Percent Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>99.9</td>
</tr>
<tr>
<td>50</td>
<td>99.8</td>
</tr>
<tr>
<td>75</td>
<td>99.7</td>
</tr>
<tr>
<td>100</td>
<td>99.5</td>
</tr>
<tr>
<td>150</td>
<td>99.2</td>
</tr>
<tr>
<td>300</td>
<td>97.4</td>
</tr>
<tr>
<td>450</td>
<td>94.8</td>
</tr>
</tbody>
</table>

5.3.0 Design guideline for diode Rectifier

5.3.1 Traction Power System calculations
1. Traction power system calculations for the existing subway lines shall be performed, as required, to determine the required capacity of the traction power substations and to verify that the voltage present at the contact shoes of operating trains is at least 450 VDC during the established contingency conditions.

2. The capacity of the substations shall be such that the functioning rectifiers, operating under the established contingency conditions, do not exceed NEMA RI9 loading for extra heavy traction service. The equivalent value, in percentage, for the overload cycle defined in the NEMA RI-9 standard for extra-heavy traction service is 160.3%. Rush hour rectifier loading should not exceed this value.

3. To verify the existing loading conditions of traction power substations, data may be obtained from the Office of Energy Management. Energy Management can provide data on the power demand of a substation in 30 minute increments (integrated demand value) for any time duration requested.

4. The following DC resistance values shall be used for various components of the traction power network when performing voltage drop calculations (verification of the 450VDC minimum):

- 3MW Rectifier : \((662V - 625V)/4800A=7.71 \text{ m}\Omega\), where 662V is the calculated average direct voltage at no load or light load as per ANSI C34.2 and 625V and 4800A are the full load ratings of the rectifier.

- 4MW Rectifier : \((662V - 625V)/6400A=5.78 \text{ m}\Omega\), where 662V is the calculated average direct voltage at no load or light load as per ANSI C34.2 and 625V and 6400A are the full load ratings of the rectifier.
2000 kcmil cable: 5.39 milliohms/1000ft.

150 lb. contact rail: 4.35 milliohms/1000ft.*

84C composite contact rail 1.50 milliohms/1000ft. *

aluminum contact rail 1.1 milliohms/1000ft*

100 lb. return rail: 9.96 milliohms/1000ft.*

* These resistance values are valid for existing rail installations. For new rail installations, contact the rail manufacturers for resistance values.

5. For the purpose of manual voltage drop calculations, the peak value of current drawn by a train during an acceleration event shall be 7000A. This represents the maximum current for a DC series motor train when the controller shifts into parallel operation. The current draw of a train, other than during the peak of an acceleration event, varies greatly. The grade of the tracks, how long an acceleration event is held and whether or not the heat or A/C is on in the cars, all affect this value. For the purpose of these calculations, where required, 3000A should be used for these “running” trains. For AC trains the peak current and “running” current values shall be obtained from the car equipment manufacturer.

6. For substation loading calculations, an equivalent RMS current per length of track, within the substation’s zone of influence, should be calculated based upon the peak rush hour headway of the subway line fed from the subject substation. An approximate rush hour loading for the substation can be obtained by multiplying all the equivalent RMS currents per length of track (within the substation’s zone of influence) by the number of tracks fed by the substation. This rush hour loading should then be compared to the available substation capacity present, when operating under the required contingency.
Figure-5.1: Elementary diagram Transformer and Rectifier
5.3.2 The Diode Rectifier

1. Rectifiers shall be of the semiconductor type using silicon diode cells. Rectifier circuitry shall be designed to provide six phase, double way, rectification generating a fundamental 12 pulse ripple (720Hz). Rectifiers shall be rated for a continuous load of either 3000KW or 4000KW.

2. Due to loading limitations on the Con Edison feeders, 3000KW is the maximum rating for newly installed, individual rectifiers in the Borough of Manhattan.

3. Each rectifier leg shall include multiple parallel diode paths such that with one path in each leg out of service, the rectifier will be capable of carrying the rated loads. Each individual silicon cell shall be hermetically sealed and mounted on an adequate air-cooled heat sink for necessary heat dissipation. The schematic on the next page indicates a typical rectifier circuit.

4. In each rectifier enclosure (up to two in a substation) provide an auxiliary transformer of either 75 or 150 KVA (dependent upon substation emergency AC load). The transformer primary shall be fed from the 490V delta phases of the rectifier transformer. The secondary of the transformer shall be 208Y/120V and shall be used for back-up low tension power. Transfer to these back-up sources shall be done through automatic transfer switches.

5. Each rectifier shall be provided with diode fuse failure monitoring. If one fuse blows in any leg, local and remote indication will be provided. If a second fuse blows in any leg, the rectifier will shut down and local and remote indication will be provided.
Figure-5.2. Rectifier Circuit for one secondary circuit

6. The power transformer and rectifier shall operate together to give a D.C. output voltage of 625 volts ± 1% at the rectifier rated output.
The regulation curves shall give the following data for the 3000kw rectifier.

Table 5.2: 3000KW Rectifier output

<table>
<thead>
<tr>
<th>OUTPUT CURRENT</th>
<th>OUTPUT VOLTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>200A</td>
<td>656-669V</td>
</tr>
<tr>
<td>4,800A</td>
<td>625V</td>
</tr>
<tr>
<td>9,600A</td>
<td>582-594V</td>
</tr>
<tr>
<td>14,400A</td>
<td>538-562V</td>
</tr>
</tbody>
</table>

The regulation curves shall give the following data for the 4000kw rectifier.

Table 5.3: 4000KW Rectifier output

<table>
<thead>
<tr>
<th>OUTPUT CURRENT</th>
<th>OUTPUT VOLTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>267A</td>
<td>656-669V</td>
</tr>
<tr>
<td>6,400A</td>
<td>625V</td>
</tr>
<tr>
<td>12,800A</td>
<td>582-594V</td>
</tr>
<tr>
<td>19,200A</td>
<td>538-562V</td>
</tr>
</tbody>
</table>

7. The rectifier assembly shall be of the indoor, free standing, metal enclosure type with hinged doors to all compartments, adequately interlocked to prevent exposure of personnel to live parts. A rectifier control cubicle, integral to the rectifier enclosure, shall be provided.

8. The rectifier enclosure shall be insulated from the floor, incoming conduits, and the substation structural steel. The enclosure shall be supported on stand off insulators.

9. The rectifiers shall be convection cooled at all loads and shall meet the loading requirements of NEMA RI-9 for extra heavy duty traction service.

10. The interphase reactor, if used, shall be mounted on the floor inside the rectifier. The base shall be installed on noise suppressing pads. The reactor shall be designed so that it is easily disconnected and removed.
11. The rectifier enclosure shall have adequate illumination.

12. The rectifier shall have smoke detectors. Smoke indication and alarm shall be provided at the Power Control Center.

13. The rectifier shall have a manual switch connected in series to the outgoing negative bus. This negative switch shall be kirk-interlocked to Device 72 (machine breaker). The interlock shall be such that in order for the negative switch to be opened, the 72 Device (machine breaker) must be opened.

6.0 SIMULINK/SIMULATION RESULT

6.1.0 Traction Power System with Uncontrolled Rectifier
Figure-6.1. Series circuit arrangement for a 12-pulse rectifier using a wye-delta and delta-delta Connected transformer to achieve the necessary 30° phase shift between 6-pulse rectifier units. From While it was relatively simple to realize the 12-pulse rectifier by taking advantage of the 30° phase shift that naturally occurs for a wye-delta transformer.
Figure-6.1: 12-Pulse Rectifier Circuit
6.1.1 Simulation common parameters for Uncontrolled Rectifier

Common parameters for Transformer:

- Transformer 1: Winding 1 Connections: Delta
  Winding 2 Connections: Delta
- Transformer 2: Winding 1 Connections: Delta
  Winding 2 Connections: Delta
- Nominal power (Pn, VA): 1663
- Nominal frequency (fn, Hz): 60
- Primary nominal voltage \( V_p \): 13.2KV (Ph-to Ph)
- Secondary nominal voltage \( V_s \): 490V (Ph-to Ph)
- Winding 1 resistance \( R_1 \) (Ohms): 1.0375
- Winding 1 inductance \( L_1 \) (H): 0.0066702
- Winding 2 resistance \( R_2 \) (Ohms): 0.0029
- Winding 2 inductance \( L_2 \) (H): 9.1914e-06
- Magnetizing branch resistance \( R_m \): 3 kΩ
- Magnetizing branch inductance \( L_m \): 2000

The universal bridges had the following common parameters for Uncontrolled Rectifier:

- Number of bridge arms: 3
- Snubber resistance \( R_s \) (Ohms): 1e5
- Snubber capacitance \( C_s \) (F): Inf.
- Power electronic device: Diodes
- On-resistance \( R_{on} \) (Ohms): 1e-3
- On-inductance \( L_{on} \) (F): 0
- Forward voltage \( V_f \) (V): 0
6.1.2 Traction Power System simulation with Uncontrolled Rectifier

Figure-6.2: Schematic diagram for 12-Pulse uncontrolled rectifier Circuit

From figure-6.2, all Cars in running condition are getting current (2800 Amps to 3600 Amps) and voltage level 450 VDC to 600 VDC.
6.1.3 Simulation Result

Figure 6.3: Constant Current

From figure 6.3: Here output constant current of each rectifier is 3800 Amps to 5200 Amps for different Subway Cars.
Figure-6.4: Subway Car Inrush current

From figure-6.4: here simulation inrush current for subway car is 8700 Amps and normal operating current is 4810 Amps.

6.2.0 Traction Power System with Controlled Rectifier

6.2.1 Simulation common parameters for Controlled Rectifier

Common parameters for Transformer:

- Transformer 1: Winding 1 Connections: Delta
  Winding 2 Connections: Delta
• Transformer 2: Winding 1 Connections: Y
  Winding 2 Connections: Delta
• Nominal power (P_n, VA): 1663
• Nominal frequency (f_n, Hz): 60
• Primary nominal voltage V_p : 13.2KV (Ph-to Ph)
• Secondary nominal voltage V_s : 490V (Ph-to Ph)
• Winding 1 resistance R_1 (Ohms): 1.0375
• Winding 1 inductance L_1(H): 0.0066702
• Winding 2 resistance R_2 (Ohms): 0.0029
• Winding 2 inductance L_2(H): 9.1914e-06
• Magnetizing branch resistance R_m : 3 kΩ
• Magnetizing branch inductance L_m : 2000

The universal bridges had the following common parameters for Uncontrolled Rectifier:

• Number of bridge arms: 3
• Snubber resistance R_s (Ohms): 1e6
• Snubber capacitance C_s (F): Inf.
• Power electronic device: IGBT
• On-resistance R_on (Ohms): 0.2e-3
• Forward voltage V_f (V): 0
6.2.2 Traction Power System simulation with Controlled Rectifier

Figure-6.5: Schematic diagram for 12-Pulse controlled rectifier circuit

Figure-6.6: Schematic diagram for 12-Pulse Controlled rectifier Circuit
6.2.3 Simulation Result

Figure-6.7: Simulation result for 12-Pulse controlled rectifier
7.0 CONCLUSION

In this thesis, 3-two unit substations were considered for simulation including four subway tracks, seven subway stations and a total of eight subway cars (Four Cars are running condition and four are starting condition). All cars in running condition are getting current (3200 Amps to 4000 Amps) and voltage level 550 VDC to 625 VDC, which is better than Traction Power with Uncontrolled system (Current level 2800 Amps to 3600 Amps, and Voltage level 450 VDC to 600 VDC).

With the controlled rectifier, the output voltage can be more controlled with adjusting the voltage. Traction power system with controlled rectifier is more effective for constant voltage and constant current is more resourceful.
LIST OF REFERENCES


