

## Power Transformer Differential Relay Inrush Restraint Setting Applications

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**Abstract:** This Paper Involves The Study Of Power Transformer Differential Relay Inrush Restraint Settings Applications. Criteria For The Setting And Testing Of Transformers Differential Relays Was Presented. The Setting Of The Inrush Restraint On A Per-Phase Basis On The Protected Transformer was Performed. The System Was Simulated Using Alternative Transient Program (Atp) Software To Examine The Level Of The Second Harmonic Presents. The Differential Relay Element Set Point For Inrush Restraint Current Was Achieved At 15% Of Second Harmonics And 35% Of Fifth Harmonics. These Settings Provide High-Speed Clearing Of Transformer Faults And Proper Restraint For Inrush Events. It's Also A Good Margin Of Security For Energization Of The Transformer Where The Second Harmonic Inrush Current Levels Are Present. These Settings Were Successful Restraining The Differential Element When Faced With A Fault Recovering Magnetizing Inrush Event. The Restraint Criterion Was Met On All Phases, As The Transformer Do Not Tripped During Energization Or Sympathetic Inrush. The Setting Is Sensitive Enough To Recognize Magnetizing Inrush Current Even With Low Levels Of Second Harmonics; And Selective To Distinguish Between An Inrush Event And Other Events That May Produce Second Harmonic Current.

**Keywords:** Power Transformer, Differential Relay, Harmonic Restraint, Energization, Magnetizing Inrush Current, Relay Setting, Current Transformer, Differential Protection.

### I. Introduction

Electric Power Utilities Have Traditionally Used Electromechanical Differential Relay For The Protection Of Power Transformers In The Past, And Many Such Relays Are Still In Use In Power Systems Today[1]. The Basic Protection For Power Transformers Is Differential protection With Second Harmonic Restraint Used To Block The differential Element During Inrush Events For The Transformer[2]. Differential Protection Is One Of The Most Reliable And Popular Techniques In Power System Protection. Differential Protection Is A Fast, Selective Method Of Protection Against Short Circuits In Transformers, And Is The Standard Protection Used By Transmission Company Of Nigeria (Tcn) To Protect Transformers. Differential Protection Is A Practical Application Of Kirchhoff's Current Law. The Sum Of The Currents Entering The Transformer Should Equal The Sum Of The Currents Leaving The Transformer. If The Net Sum Of The Currents That Enter And The Currents That Leave A Protection Zone Is Essentially Zero, It Is Concluded That There Is No Fault In The Protection Zone. However, If The Net Sum Is Not Zero, The Differential Protection Concludes That A Fault Exists In The Zone And Takes Steps To Isolate The Zone From The Rest of The System. Differential Protection Compares The Measured Currents Entering And Leaving The Transformer To Create A Differential Current. With The Ideal Transformer Of Figure 1, And Assuming Ideal Current Transformers, The Differential Current Is Zero When Current Is Flowing Through The Transformer. Differential Current Greater Than Zero Indicate An Internal Fault Condition. In Practice, The Differential Current For A Normally Operating Transformer Is Always Greater Than Zero Due To Ct Measurement Error And The Position Of The Load Tap Changer [3]. Misoperations Can Occur During Energization Of A Transformer Due To Failure Of The Harmonic Restraint Function. An External Fault Can Also Trigger A Misoperation During The Voltage Recovering Period, Causing The Differential Relay To Operate Immediately After A Fault Is Cleared From The System.

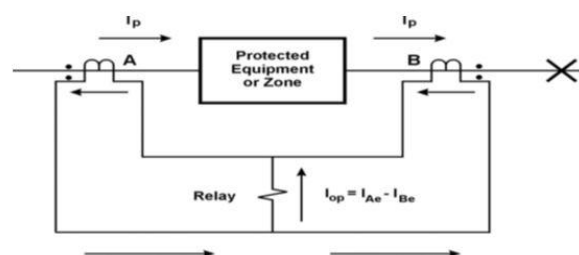


Figure 1: Transformer Differential Protection Principle

There Are Two Common Situations Where Differential Protection may Incorrectly Declare An Internal Fault Condition. One Condition is Ct Saturation For A Fault Outside Of The Transformer Zone Of protection. The Error In The Measured Signal Of The Saturated ct Results In A Significant Error In The Differential Current. The erroneous Differential Current May Result In Undesired Operation of The Differential Element For An External Fault Condition. The Second Common Situation Is A Transformer Inrush Event. Some Operating Situations Instantly Change The Operating Flux of The Transformer Core, Requiring A Large Supply Of Current. This Inrush Of Current Typically Occurs In Only One Winding Of the Transformer. Therefore Inrush Currents May Produce A differential Current That Results In The Operation Of The Differential protection. This Type Of Event Is Not A Fault Condition, So The differential Protection Should Restrain From Operating For This condition. This Paper Intends To Discuss The Setting Of Inrush Current Due To Harmonic In Power Transformers.

## II. General Description

Any Event On The Power System That Causes A Significant Increase In The Magnetizing Voltage Of The Transformer Core Results In Magnetizing Inrush Currents Flowing Into The Transformer. The Three Most Common Events Are energization Of Transformer, Magnetizing Inrush Current And Sympathetic Inrush. These Are Discussed In The Session That Follows.

### Energization Of Power Transformer.

This Is The Typical Event Where A Magnetizing Inrush Current Is Of Concern. The Excitation Voltage On One Winding Is Increased From 0 To Full Voltage. The Transformer Core Typically Saturates, With The Amount Of Saturation Determined By Transformer Design, System Impedance, The Remnant Flux In The Core, And The Point On The Voltage Wave When The Transformer Is Energized. The Current Needed To Supply This Flux May Be As Much As 20 Times The Full Load Rating Of The Transformer, With Typical Value For Power Transformers For 6 Times The Full Load Rating [3]. Transformer Energization Is A Typical Cause Of Inrush Currents, But Any transient In The Transformer Circuit May Generate These Currents. Other Causes Include Voltage recovery After The Clearance Of An External Fault Or The Energization Of A Transformer In Parallel with A Transformer That Is Already In Service. The Magnitudes And Waveforms Of Inrush Currents depend On A Multitude Of Factors, And Are Almost Impossible To Predict. The Following summarizes The Main Characteristics Of Inrush Currents:

- Generally Contain Dc Offset, Odd Harmonics, And Even Harmonics [4, 5].
- Typically Composed Of Unipolar Or Bipolar Pulses, Separated By Intervals Of Very Low Current Values.
- Peak Values Of Unipolar Inrush Current Pulses Decrease Very Slowly. Time Constant Is Typically Much Greater Than That Of The Exponentially Decaying Dc Offset Of Fault Currents.
- Second-Harmonic Content Starts With A Low Value And Increases As The Inrush Current Decreases.

Figure 2 Show Equivalent Circuit Of A Transformer. In An Ideal transformer, The Primary And Secondary Currents  $I_p$  And  $I_s$  Are equal Except For The Small Current Flowing Through The Shunt element Of The Magnetizing Branch. The Increase In Flux Caused by An Increase In The Exciting Voltage Draws More Current through The Magnetizing Branch. When The Transformer Is being Energized, This Current Flows Through Only One Winding.

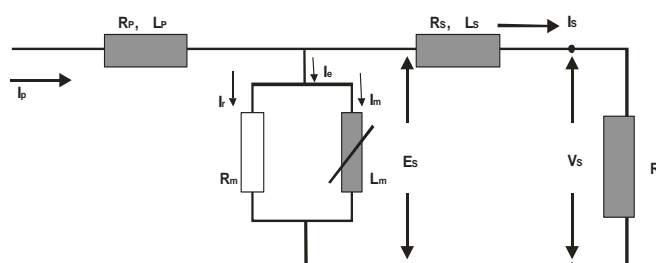


Figure 2: Transformer Equivalent Circuits

During Inrush Events Other Than Energization, The Magnetizing Inrush Current May Appear In Both Windings, With The Inrush Current More Prevalent In One Winding As Show In figure 3. An External Magnetizing Force Causes All The Magnetic Moments Of The Steel To Align With The Applied Magnetic Field. In The Case Of Transformers, The Excitation Voltage Provides This Applied Magnetic Field. The Alignment Of The Magnetic Moments Causes An Increase In Flux Density Greater Than That Of The External Magnetic Field. The Steel Is Fully Saturated When All The Magnetic Moments Are Aligned With The Applied Field. The Magnitude And Characteristic Of The Inrush Current Is Dependent On The Amount Of Saturation Of The Transformer Core.

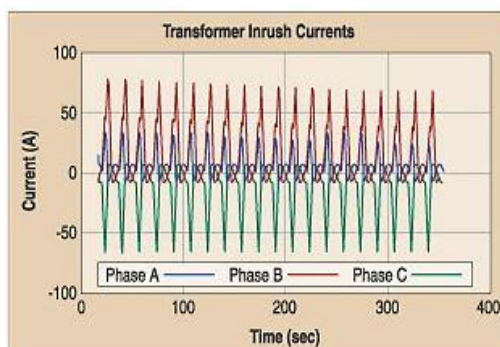


Figure 3: Magnetization Inrush Current Characteristic In A Power Transformer

### Magnetizing Inrush Current

An External Fault May Significantly Reduce The System Voltage, And Therefore Reduce The Excitation Voltage Of The Transformer. When This Fault Is Cleared, The Excitation Voltage Returns To The Normal System Voltage Level. The Return Of Voltage May Force A Dc Offset On The Flux Linkages, Resulting In Magnetizing Inrush Current. This Magnetizing Inrush Current Will Be Less Than That Of Energization, As There Is No Remnant Flux In The Core[8]. The Current Measured By The Differential Relay Will Be Fairly Linear Due To The Presence Of Load Current, And May Result In Low Levels Of Second Harmonic Current. If The Transformer Were Reenergized At The Instant The Voltage Waveform Correspond To The Residual Magnetic Density Within The Core, There Would Be A Smooth Continuation Of The Previous Operation With No Transients. However, In Practice, The Instant When Switching Takes Place Cannot Be Controlled, And A Magnetizing Transient Occurs, Almost Inevitably.

The Transient Generates A Current Known As Inrush Current. The Magnitude Of This Inrush Current Can Be Several Times The Load Current And Flows Only On One Side Of The Differential Relay, Which Tends To Operate If Some Form Of Restraint Is Not Provided. Inrush Currents Measured In Separate Phases Of A Three-Phase Transformer May Differ Considerably Because Of The Following [9]:

- The Angles Of The Energizing Voltages Are Different In Different Phases.
- When The Delta-Connected Winding Is Switched-In, The Line Voltages Are Applied As The Magnetizing Voltages.
- In The Later Case, The Line Current In A Given Phase Is A Vector Sum Of Two Winding Currents.
- Depending On The Core Type And Other Conditions, Only Some Of The Core Legs May Get Saturated.

### Sympathetic Inrush.

Energizing A Transformer On The Power System Can Cause Sympathetic Magnetizing Inrush Currents To Flow In An Already Energized Parallel Transformer. Energizing The Second Transformer As Shown In Figure 4(A) Causes Voltage Drop Across The Resistance Of The Sourcefeeding The Transformers. This Voltage Drop May Cause A Saturation Of The Already Energized Transformer In The Negative Direction. This Saturation Causes Magnetizing Inrush Current To Supply The Flux. The Magnitude Of The Magnetizing Inrush Currents Is Generally Not As Severe As The Other Cases[5, 6,7].

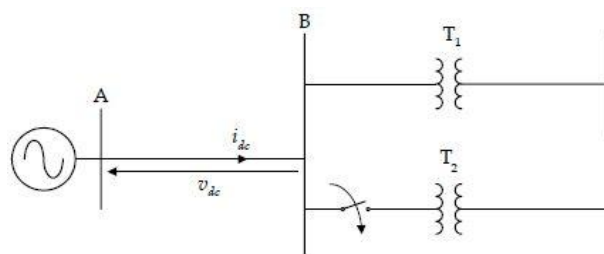


Figure 4: (A) Sympathetic Inrush Circuit

Figure 4 (B) Shows A Typical Set Of Transformer Inrush Waveforms Captured During The Energization Of The 60mva, 132kv/33kv Power Transformer, Energized At 132kvdelta/Star Transformer.  $I_b$  And  $I_c$  Are Fully Offset, And  $I_a$  Shows The Typical Effects Of Interphase Coupling And Highly Non-Sinusoidal. Magnetizing Inrush Current Under Normal Operating Conditions Is Very Small. However, When A Transformer Is Energized After It Has Been Taken Out Of Service, The Magnetizing Inrush Current Can Be Extremely Large As 10 Times Full Load Current For A Short Period (Say 5 Cycles). Closer Examination Of

These Waveforms, With Harmonic Analysis, Shows That All Of These Waveforms Have A Strong Second-Harmonic Component, With A Fourth-Harmonic Component, The Next Most Prevalent Harmonic, In Two Out Of The Three Phases [11, 12].

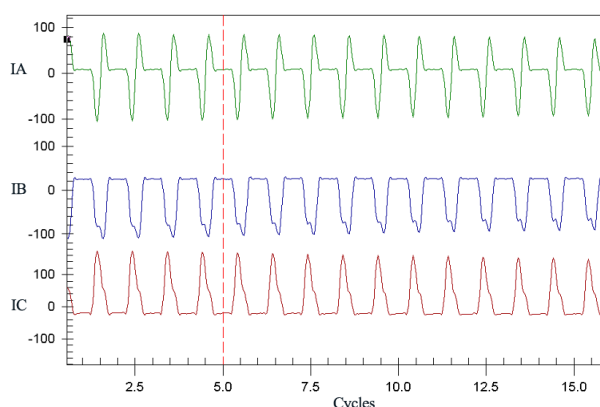


Figure 4: (B) Typical Set Of Transformer Inrush Waveforms

### Analysis Of Differential Relays Setting

Harmonic Restraint Is The Classical Way To Restrain Relay Tripping. The Techniques Work On The Principle that The Magnetizing Inrush Current Contains High Levels Of Second Harmonic Current. The Current For An Internal Transformer Fault Typically Has Very Low Levels Of Second Harmonic Current. The Simplest Method Of Harmonic Restraint Uses The Magnitude Of The Second Harmonic In The Differential Current Compared To The Magnitude Of The Fundamental Frequency Component In The Differential Current. Tripping Of The Differential Element Is Blocked When This Ratio Exceeds An Adjustable Threshold. The Historical Setting For Harmonic Restraint Is A Second Harmonic Ratio Of 15%, With An Available Setting Range Of 1% To 40%. When Set Too High, The Differential Element Trip During Transformer Energizing; And If Set Too Low, The Inrush Restraint May Block Tripping During Some Internal Fault Events.

Ideally, Setting The Inrush Restraint Function For The Transformer Differential Element Is Exactly Like Setting Any Other Protection Function. The Key Criteria Are Sensitivity And Selectivity. The Setting Must Be Sensitive Enough To Recognize Magnetizing Inrush Current Even With Low Levels Of Second Harmonics. And It Must Be Selective To Distinguish Between An Inrush Event And Other Events That May Produce Second Harmonic Current. The Standard Process For Setting A Protection Function Is To Perform An Analysis Of The System. This Analysis Models The Response Of The System For Various Transient Events To Provide A Basis For Setting Protection Functions.

The Power Transformer Under Analysis Is A 60mva, 132kv/33kv Delta/Star Connected And Energized

At 132kv. The Full Load Current  $I_{FL} = \frac{S_{max} * 1000}{\sqrt{3} * KV}$

Where Smax = Transformer Apparent Power In Mva,

Kv = Line Voltage In Kilovolts

Thus For Delta Connected Winding,  $I_{FL} = \frac{60 * 1000}{\sqrt{3} * 132} = 262.44$  Amps.

Select Current Transformers (Cts) Of 300:5a Ratio For The Primary Windings.

Ct Secondary Current To The Relay Is  $I_{relay} = \frac{I_{Fl}}{C_{tr}} = \frac{262.44 * 5}{300} = 4.374$

For Star Connected Winding,  $I_{FL} = \frac{60 * 1000}{\sqrt{3} * 33} = 1049.76$  Amps.

Select Current Transformers (Cts) Of 1200:5a Ratio For The Primary Windings.

Ct Secondary Current To The Relay Is  $I_{relay} = \frac{I_{Fl}}{C_{tr}} = \frac{1049.76 * 5}{1200} = 4.374$  Amps.

Result Show That The sum Of The Currents Entering The primary Restraint Windings Of The Differential Relay Equals The Sum Of The Currents Leaving The Secondary restraint winding; Hence The Differential Relay Operating Current Is Zero. This Concludes That There Is No Fault In The Protection Zone.

### Differential element Setting

An Instantaneous (High Set) Differential Element Remove The Transformer quickly From Service In The Event Of Severe Internal Faults And To Eliminate The Effects Of Dc Offsets And Harmonics, The Relay Trips On The Sensing Of Sequential Positive And Negative Peak Currents Whose Magnitude Exceeds The High Set Trip Level. This Element Operates Within 15 Milli-Seconds. During Transformer Energization, Significant 2nd Harmonic Current Is Present, Which May Result In False Trips. This Requires The Relay To Suppress Its Response To The 2<sup>nd</sup> Harmonic Component Of Current. The Differential Relay Allows For Adjustment Of The 2nd Harmonic Restraint Element Over The Range Of 0.1 To 0.3 P.U. Of The Transformer's Rated Current. Similarly, Over-Excitation Of The Transformer Results In Significant Levels Of 5th Harmonic Current. For Transformer Protection Applications These Settings Provide High-Speed Clearing Of Transformer Faults And Proper Restraint For Inrush Events. For A Few Applications, Lowering The Harmonic Restraint Setting, Is Necessary To Ensure That Transformer Energization Occur Successfully Where Very Low Second Harmonic Inrush Levels Are Present.

### Testing Of Inrush Restraint Methods

To Determine The Most Appropriate Choice For The Inrush Restraint Method And The Inrush Restraint Mode, A Simple Laboratory Experimental Procedure Was Performed Along With Actual Operating Experience To Develop The Standard Settings For The Inrush Restraint Function. The Schweitzer Engineering Laboratories (SEL-487) Microprocessor-Based Relay Type Was Configured To Some Inrush Restraint Function And Level Setting Method.

The Procedure Was To Simply Choose Some Settings For The Relay, Connect The Relay To A Three-Phase Test Set, And Simulates The System Using Alternative Transient Program (ATP) Software To Examine The Level Of The Second Harmonic Presents. Figure 5(A) Shows Waveform Of Inrush Current And (B) Mal-Operation Of A Differential Relay Caused By Low Levels Of The Second Harmonic Current During Energization Of A Transformer.

These Tests Were Repeated Using Different Set Points And Different Restraint Functions Until A Standard Setting Operating Criteria Was Determined. This Standard Package Of Settings Was Confirmed By Capturing Transformer In-Rush Records From Various Installations And Comparing The Set Point Levels To Actual Second Harmonic Levels To Confirm There Is Enough Margins.

Before Beginning The Setting And Testing, We Set The Following Criteria For Acceptable Settings.

- A Minimum Level Setting For Harmonic Restraint At 15%.
- No Operating Time Delay For The Differential Element Is Introduced By The Selected Inrush Restraint Function Or Inrush Restraint Mode.
- The Differential Element Is Blocked From Operating During This Actual Energization Event.

In Addition, The Inrush Restraint Mode Was Implemented Using The Flexible Configuration Logic Of The Relay. This Test Procedure Uses Star-Connected Cts That Are Typical On New Installations Using Microprocessor-Based Differential Relays.

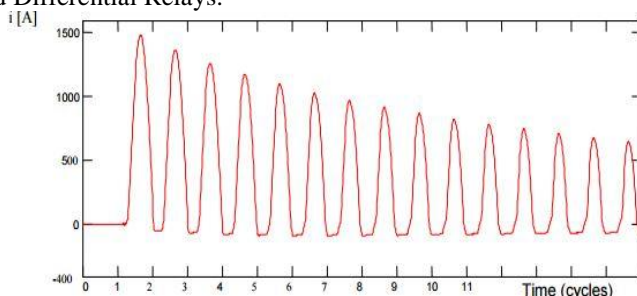


Figure 5: (A) Inrush Current

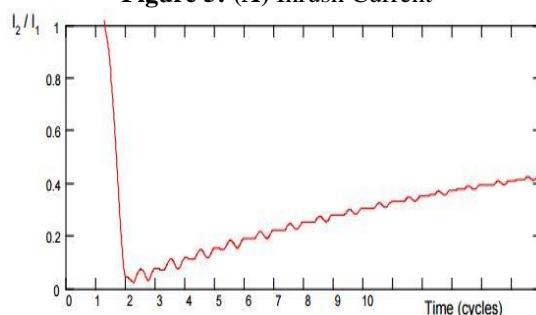


Figure 5: (B) Second Harmonics during Energization Characteristic

### III. Results And Discussion

The Differential Relay Element Set Point For The Inrush Restraint Current Was 15% Of Second Harmonics, While The Fifth Harmonics Was Set At 35%. These Settings Provide A Good Margin Of Security For Energization Of The Transformer Where The Second Harmonic Current May Fall To Low Levels. The Settings Were Successfully Restraining The Differential Element When Faced With A Fault Recovery Magnetizing Inrush Event. The Operation Of The Differential Element On Any Phase Operates The Circuit Breakers Supplying The Transformer. The Restraint Criterion Was Met On All Phases, As The Transformer Do Not Tripped During Energization Or Sympathetic Inrush. For This Application, The Magnetizing Inrush Currents During Energization Of The Transformer Were High Enough To Cause Operation Of The Differential Element. Result Show That The Sum Of The Currents Entering The Primary Restraint Windings Of The Differential Relay Equals The Sum Of The Currents Leaving The Secondary Restraint Winding; Hence The Differential Relay Operating Current Is Zero. This Concludes That There Is No Fault In The Protection Zone.

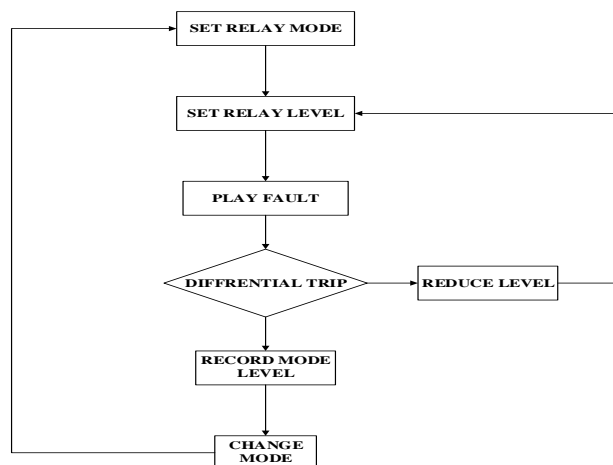
The Results Of The Sel-487 Microprocessor-Based Differential Relay Field Configuration And Harmonic Restraint Settings Are Tabulated In Table 1 and 2, And Detailed Test Procedure Flow Chart Is Shown In Figure 6. These Results Match The Expected Results For The Different Inrush Restraint Modes.

Table 1: Sel-551 Relay Differential Settings (Field Configuration)

Setting Label	Definition	Limits
Rid	Relay Identifier	Sap- 1
Tid	Terminal Identifier	Line 1
E87w1-A,	Enable Winding 1-A In Differential	Yes
E87w1-B,	Enable Winding 1-B In Differential	Yes
E87w1- C.	Enable Winding 1-C In Differential	Yes
E87w2-A,	Enable Winding 2-A In Differential	Yes
E87w2-B,	Enable Winding 2-B In Differential	Yes
E87w2-C.	Enable Winding 2-C In Differential	Yes
W1ct-A,	Winding 1-A, Ct Connection (Delta, Star)	Star (Y)
W1ct-B,	Winding 1-B, Ct Connection (Delta, Star)	Star (Y)
W1ct-C.	Winding 1-C, Ct Connection (Delta, Star)	Star (Y)
W2ct-A,	Winding 2-A, Ct Connection (Delta, Star)	Star (Y)
W2ct-B,	Winding 2-B, Ct Connection (Delta, Star)	Star (Y)
W2ct-C.	Winding 2-C, Ct Connection (Delta, Star)	Star (Y)
Mva	Maximum Transformer Capacity, Three-Phase	60 Mva
Ctr1-A,(Pri)	Winding 1-A, Ct Ratio (Ipri/In)	300:5 A
Ctr1-B,( Pri)	Winding 1-B, Ct Ratio (Ipri/In)	300:5 A
Ctr1-C,( Pri)	Winding 1-C, Ct Ratio (Ipri/In)	300:5 A
Ctr2-A,( Sec)	Winding 2-A, Ct Ratio (Isec/In)	1200:5 A
Ctr2-B,( Sec)	Winding 2-B, Ct Ratio (Isec/In)	1200:5 A
Ctr2-C,(Sec)	Winding 2-C, Ct Ratio (Isec/In)	1200:5 A
Icom	Define Internal Winding / Ct Connection Compensation	Star (Y)
W1ctvg	Winding 1a,B,C (Delta) Vector Group Compensation	Dyn 1, (Dab)
Vwdg1	Winding 1a,B,C Line Voltage, Kv	132kv
Vwdg2	Winding 2a,B,C Line Voltage, Kv	33kv
Wdg1(Pri) I	Winding 1a,B,C Line Currents (Amps)	262.44
Wdg2(Sec) I	Winding 2a,B,C Line Currents (Amps)	1049.76
Nfreq	Nominal Frequency Hz	50 Hz,
Phrot	Phase Sequence Rotation	Abc,
Date-F	Month/Day/Year Format	Mdy

Table 2: Differential Elements Relay Settings (Harmonic Restraint Results).

Display	Descriptions	Setting
Wdg1(Pri)	Winding 1(A,B&C) Currents( 0.5 - 155 A Secondary)	4.374
Wdg2(Sec)	Winding 2(A,B&C) Currents( 0.5 - 155 A Secondary)	4.374
087p	Restrained Element Operating Current P.U	0.3
Slp1	Restraint Slope 1 Percentage (5 – 100%)	25
Slp2	Restraint Slope 2 Percentage (Off, 25 – 200%)	50
Irsi	Restraint Current Slope 1 Limit ((1-20) Multiple Of Tap)	3
U87p	Unrestrained Element Current Pu((1-20) Multiple Of Tap)	10
Pct2	Second- Harmony Blocking Percentage (Off, 5-100%)	15
Pct5	Fifth- Harmony Blocking Percentage (Off, 5-100%)	35
Th5p	Fifth- Harmony Alarm Threshold (Off, 0.02 -3.2)	Off
Ihbl	Independent Harmonic Blocking (Y, N)	Nil



**Figure6:** Differential Relay Test Procedures Flow Chart

#### Advantages Of Microprocessor-Based Differential Relay Protection

- High Stability Against Ct Saturation Provided By Integrated Saturation Detector And Add-On Stabilization
- High Stability Against Inrush Currents Due To Advanced Filter Technology And Optional Cross-Blocking Function.
- High Stability Against Over-Excitation ( 5th Harmonic Blocking)
- Short Tripping Time - Typically 1.5 Cycles
- High Set Fast Tripping Less Than One (1) Cycle
- Sensitive Earth Differential Protection Against Interturn Faults And Earth Faults Near Winding Neutral
- Integral Ratio And Vector Group Adaptation
- Integral Thermal Overload Protection
- External Start Of Fault Recording

#### IV. Conclusions

The Settings Of Inrush Restraint For Transformer Differential Protection Used Harmonic Restraint In A Per-Phase Mode, With A Restraint Level Of 15% Of Second Harmonics And 35% Of Fifth Harmonics. These Settings Provide High-Speed Clearing Of Transformer Faults And Proper Restraint For Inrush Events. Lowering The Harmonic Restraint Settings ensure That Transformer Energizations Occur Successfully Where Very Low Second Harmonic Inrush Levels Are Present. The Operation Of The Differential Element On Any Phase Operates The Circuit Breakers Supplying The Transformer. The Restraint Criterion Was Met On All Phases, As The Transformer Do Not Tripped During Energization Or Sympathetic Inrush. The Setting Is Sensitive Enough To Recognize Magnetizing Inrush Current Even With Low Levels Of Second Harmonics; And Selective To Distinguish Between An Inrush Event And Other Events That May Produce Second Harmonic Current. The Magnetizing Inrush Currents During Energization Of The Transformer Were High Enough To Cause Operation Of The Differential Element. The Sum Of The Currents Entering The Primary Restraint Windings Of The Differential Relay Equals The Sum Of The Currents Leaving The Secondary Restraint Winding; Hence The Differential Relay Operating Current Is Zero. This Concludes That There Is No Fault In The Protection Zone. Harmonic Blocking Or Harmonic Restraint Elements Permit Fast Tripping For All Internal Transformer Faults With Minimal Delay When Energizing A Faulted Transformer; Prevent Transformer Differential Relay Operation During Transformer Over Excitation, Prevent Differential Element Operation During Transformer Energization And During Voltage Recovery Following A Power System Fault.

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