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A Reliability Analysis Of Supercapacitor Energy Storage In Multi Engine Unlimited Bus Systems Using The Critical Paths Method

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ABSTRACT

In modern industry, industrial revolution 4.0, energy storage systems are becoming increasingly important to support reliable and efficient performance. One of the technologies used in energy storage systems is supercapacitors. where Supercapacitors offer advantages in terms of high energy charging and discharging speeds, long service life, and the ability to withstand extreme temperatures. One of the characteristics of this power plant is the instability of the power released by this plant due to varying wind speeds. One solution to overcome this is to add energy storage to the generating system which works as power smoothing so that the power sent to the load can be maintained constant. This system can work as an energy store when the power released by the generator exceeds the power required by the load and can be an energy source when the power released by the generator is less than the power required by the load. The problem with energy storage in general is that the usage cycle tends to be low. Supercapacitors, with their characteristics of high power density, high efficiency and high usage cycles, are considered capable of overcoming the problems of other energy storage systems. This final project contains a study of the use of supercapacitors as energy storage in wind power plants, with a focus on comparing several parameters of supercapacitors with lead acid batteries. Based on the simulation results in this research, it can be concluded that supercapacitors have a power density and number of life cycles that tend to be higher than batteries, but have disadvantages, including a small energy capacity and relatively more expensive costs compared to batteries. Supercapacitors can also work as power smoothers to keep power on the DC link constant.

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INTRODUCTION

In the modern transportation industry, energy storage systems play an important role to support reliable and efficient performance. One of the technologies used in energy storage systems is supercapacitors. Supercapacitors have advantages in terms of high charging and discharging speeds, long service life, and the ability to withstand extreme temperatures.

In public transportation systems such as electric buses, supercapacitors are used as part of an energy storage system to handle energy regeneration during braking, provide additional power when needed, and optimize overall energy use. However, to ensure reliable performance, careful reliability analysis of supercapacitor energy storage in the context of seamless multi-machine bus systems is required.

The current operation of the electric power system must be in an optimal state. Good power system design and operation is determined by several things: the system's ability to cope with changes in power demand, both active and reactive power; operates with minimum costs and minimal environmental impact; and power source quality, such as constant frequency and voltage and high reliability.

However, this condition cannot always be met because the electric power system often experiences disturbances, both large and small. This interference can cause stability problems. Electric power system stability is defined as the ability of a power system to return to a normal state after experiencing a disturbance, with many variables being limited. The most critical stability is transient stability.

Transient stability analysis can be carried out using numerical integration to obtain the dynamic response to disturbances. This method is effective for complex systems and for complex non-linear phenomena. However, numerical integration takes a long time in the process. To speed up the calculation process, the energy function method is introduced, which assesses system stability based on energy during transient times. This method calculates the critical energy and evaluates it, although it cannot handle transient problems in complex power systems accurately.

A new method called the Critical Path Method is used to analyze transient stability based on the critical path formed from the moment the disturbance occurs until before the system loses its synchronization, or critical point. This critical point is called the Unstable Equilibrium Point (UEP). This method uses trapezoidal equations for numerical integration calculations and simultaneous equations to speed up the calculation process.

The Critical Path Method has been applied in several power systems with loop configurations with a fairly good level of effectiveness. The loop configuration is used in the transmission system in Indonesia, while the radial configuration is in the distribution system. Industrial systems can use both configurations, either loop or radial. The continuing development of power systems has given rise to the idea of a smart power system (Smart Grid) that is reliable and has advantages over conventional power systems. Smart Grid is designed to deal with various electric power system problems. This research will analyze transient stability problems that occur in the Smart Grid using the critical path method.

Literature Review

Permanent Magnet Synchronous Generator (PMSG)

Generators are one of the important equipment needed in an electricity generation system. The generator functions as a conversion tool from mechanical energy to electrical energy. One alternative that can be chosen in power plants that utilize new, renewable energy is the Permanent Magnet Synchronous Generator (PMSG). including:

1. Having no brushes and slip rings, this type of generator has a shape and a small moment of inertia
2. Has a simple shape but high efficiency

3. The magnetic flux contained in this generator comes from the permanent magnet it has and also does not have a rotor winding. This makes PMSG produce a high density so that it can reduce the size and size weight.
4. Does not require external excitation generator, so there are no copper losses in the rotor circuit, and maintenance costs tend to be low.
5. High reliability
6. If there is interference on the grid, it does not affect it generator directly due to amplitude and frequency the voltage is fully controlled by the power converter

However, PMSG also has disadvantages, including:
1. Permanent magnetic materials tend to be expensive
2. Complicated fabrication process
3. The removal process for permanent magnets requires temperature tall one
4. Highly dependent on power converters, because of all the power generated must go through a power converter
5. Has high losses in electronic circuits

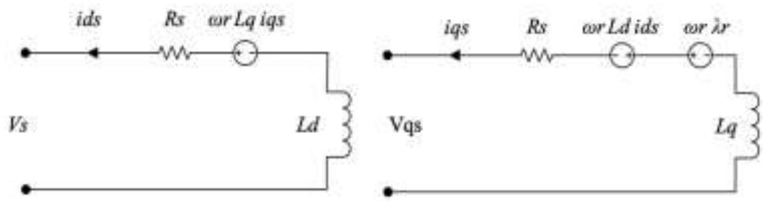

Figure 1. Permanent Magnet Synchronous

The PMSG dynamic model is described in the equivalent circuit dq as shown in Figure. Based on this circuit, the following equations are obtained which express the stator voltage on the d axis and the stator voltage on the q axis:

Where :

ids = d-axis stator current
iqs = q-axis stator current
Rs = winding resistance
Ld = winding inductance on the d axis
Lq = winding inductance on the q axis
p = number of poles
$vds = -ids.Rs - \omega_r\ Lq.iqs - p.Ld.ids$
$vqs = -iqs.Rs - \omega_r\ Ld.ids - p.Lq.iqs$
ω_r = PMSG electrical rotation speed (rad/s)

Energy Storage

The wind turbine system is very dependent on the speed of the wind that drives the wind turbine to be converted into electrical energy. Fluctuating wind speed causes the power produced to fluctuate, this fluctuating power causes fluctuating frequencies and voltage flickers in the system. Apart from that, stable power is needed that matches the load requirements. For this reason, a mechanism is needed that can work as a power balancer when there is excess power or lack of power in the system so that the power produced by the wind turbine system is constant, this is what is called power smoothing.

Energy storage is an alternative component that can be used to act as a power balancer or power smoother produced by a wind energy conversion system. Energy storage is capable of carrying out a charging mechanism, when the power produced by the wind turbine exceeds the power required by the load, and can carry out a discharging mechanism when the power required by the load exceeds the power capable of being produced by the wind turbine. In this final assignment, research was carried out comparing batteries and supercapacitors as energy storage in wind turbine systems.

Battery

Batteries are one component of an energy storage system that can be chosen as an alternative to obtain a power balance between the power produced by the wind turbine system and the power required by the grid through charging and discharging from and/or to the energy storage system. This.

Batteries are one of the oldest and most widely used energy storage technologies to date, because they are quite effective for small and high power applications. A battery consists of two or more cells connected in a series or parallel arrangement to obtain a certain required capacity and operating voltage. Batteries have high charge and discharge efficiency, long service life, and relatively low cost.

One of the commonly used batteries is Lead Acid. This battery has relatively low performance at temperatures that are too high or too low and the lifespan of this battery tends to be short. These batteries are generally found as energy storage systems in photovoltaic applications, especially in stand-alone systems because they are easy to carry anywhere. In this final project, a generic lead acid battery model is used in MATLAB/Simulink which can be observed in Figure 2 below.

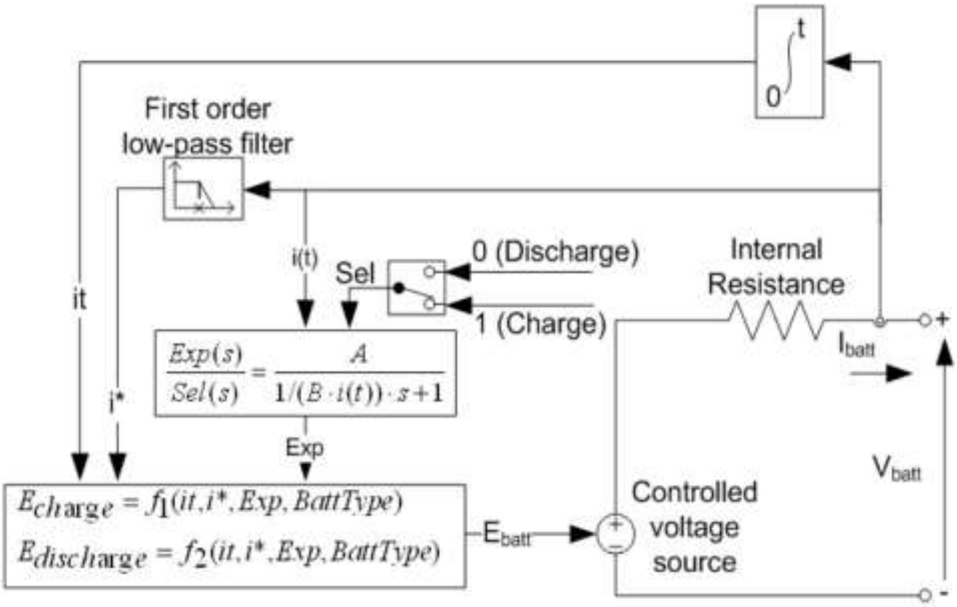

Figure 2. MATLAB/Simulink Generic Lead Acid Battery Modeling

As energy storage, batteries have a characteristic curve of voltage to state of charge (SOC) during the charging and discharging process. Batteries have voltage characteristics that tend to be constant with changes in their SOC.

Supercapacitor

Supercapacitors, or what are usually called ultracapacitors, are included in one category of electro-chemical energy storage media. First discovered in SOHIO (Standard Oil Company of Ohio) by Robert A. Rightmire. This discovery begins with the use of an electrostatic field to cross the interphase boundary, between electrons and ions in the conductor to increase energy storage using the principle of ionic adsorption at the interphase boundary.

Supercapacitors have several times the capacitance compared to conventional capacitors. The principles used in supercapacitors follow the same basics used in conventional capacitors. However, in supercapacitors the electrode surface is made larger and also has a thinner thickness so that the distance between the two electrode pieces is thinner.

This has an impact on the amount of capacitance and energy that supercapacitors can store compared to conventional capacitors, they also have higher power density, shorter charging times and longer shelf life cycles than ordinary batteries. In this final project, generic supercapacitor modeling is used in MATLAB/Simulink as can be observed in Figure 3.

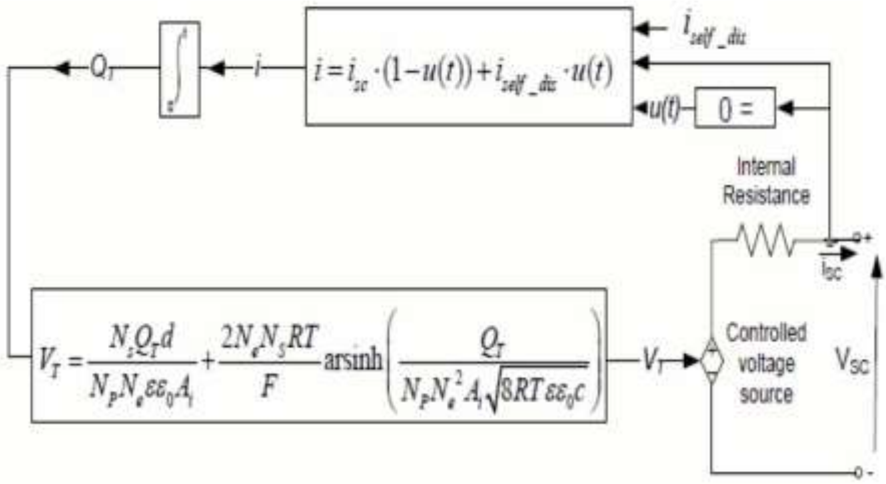

Figure 3. Generic Simulink Supercapacitor Modeling

METHOD

Switching overvoltage modeling will be modeled using ATPDraw software simulation. Transient overvoltage that occurs due to the process of providing power to a transmission line depends on the characteristics of the transmission line used. Overvoltage disturbances in the transmission and distribution of electric power systems are usually caused by two types of surge voltage, namely lightning surges and circuit surges which have amplitudes greater than the nominal peak voltage value. One source of circuit surge overvoltage is the opening and closing of circuit breakers. The magnitude of the voltage amplitude during load shedding always correlates with the system voltage and the oscillation frequency which is

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influenced by the system impedance. The phenomenon of circuit surges on transmission lines can be resolved by creating a single phase equivalent circuit. So each phase is assumed to be able to stand alone, this applies if the power cutoff on each phase closes simultaneously. The simulation that will be carried out is by providing a three-phase fault trigger to the ground with the assumption that the circuit breaker is opened.

In this study, a simulation was carried out to determine the transient recovery voltage response that occurs in a 20 kV medium voltage switching circuit breaker so that it is necessary to model the system circuit as in Figure 3.2 which will be modeled as Figure 3.3 using ATPDraw software.

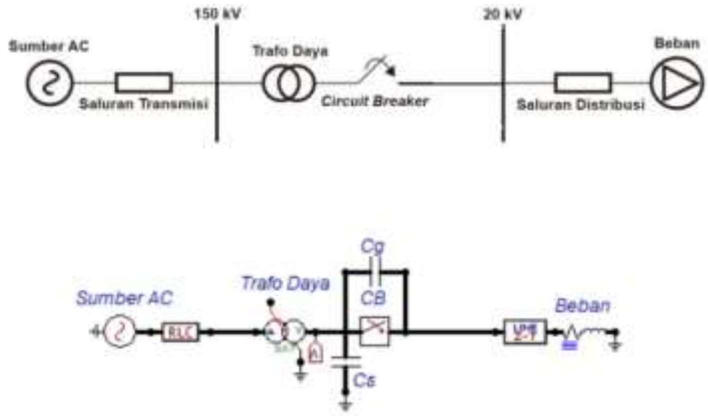

Figure 4. Single Line Switching Circuit Breaker Circuit Diagra *Breakers*

For system modeling, 3 different types of power transformer winding connections are used, viz

1. The power transformer uses a Delta – Wye type winding.
2. The power transformer uses a Wye – Delta type winding.
3. The power transformer uses a Delta – Delta type winding.
4. The power transformer uses a Wye – Wye type winding.

Carrying out a simulation using the type of power transformer winding connection is intended to find out the differences between *transient recovery voltage*resulting from. So the characteristics of the traveling waves that occur are also known. Transient Recovery Voltage generated during the circuit breaker disconnection process will be analyzed using waves with the input parameters beingVL–N peakthe secondary side of a power transformer differs based on the type of winding connection. After the characteristics of the reflected wave are known, the results will be compared with the Transient Recovery Voltage.

Table 1. Circuit Parameters

Parameter	Mark	Unit
Voltage Source	150	kV
Frequency	50	Hz
Grading Capacitance(CG)	0.05	μF
Shunt Capacitance(Cs)	1	μF
Circuit breaker	0.1	s

Parameter	MarkUnit
Short circuit switching	0.05 s

Based on the single line circuit diagram of 20 kV medium voltage transmission as in Figure 3.2 above, a transient recovery voltage circuit model was created with different power transformer winding connections to determine the differences in transient recovery voltage responses shown in Figure 3.4, Figure 3.5, Figure 3.6, and Figure 3.7 . The circuit modeling is equipped with a trigger in the form of a switching which is then connected to ground to model the short circuit system. This circuit modeling consists of main components such as a 150 kV voltage source, resistors, capacitors, nonlinear inductors, circuit breakers, power transformers with the circuit parameters shown in Table 3.1. Circuit modeling is carried out in the Alternative Transient Program or ATPDraw. The aim of modeling this transient recovery voltage circuit is to determine the differences in transient voltage response when switching a medium voltage circuit breaker and determine the differences in traveling wave response which will be analyzed using the lattice Bewley diagram method using MATLAB software.

The parameters used in each component are shown in Table 1 and Table 2. Then the circuit modeling uses a power transformer which is used to reduce the voltage from source voltage to medium voltage. The power transformer used is a three-phase step-down power transformer with a voltage rating of 150 kV / 20 kV. The power transformer parameters used in this study were taken from the references shown in Table 2.

Table 2. Power Transformer Parameters

Parameter	Mark	Unit
Primary Resistance	220	Ω
Primary Inductance	1,745	mH
R magnetization	6500000	Ω
Secondary Resistance	5	Ω
Secondary Inductance	0.039	mH

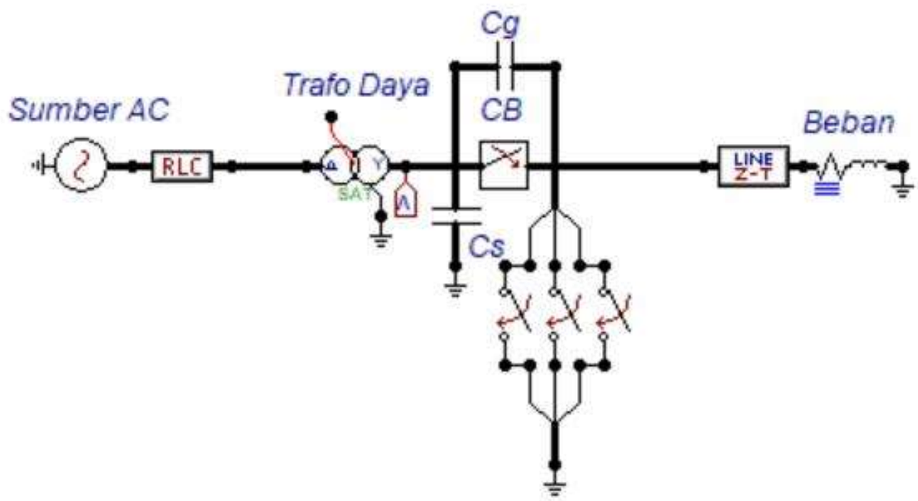

Figure 5. Circuit Modeling with Delta-Wye Power Transformer Windings in Switching Circuit Breaker Conditions

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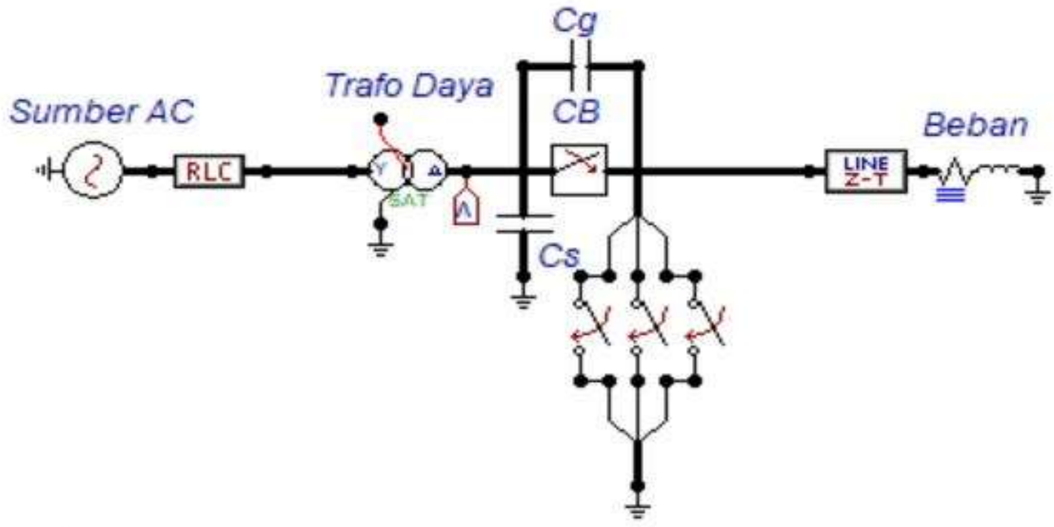

Figure 6. Circuit Modeling with Windings
Power Transformer *Wye-Delta* on Condition *Switching Circuit Breakers*

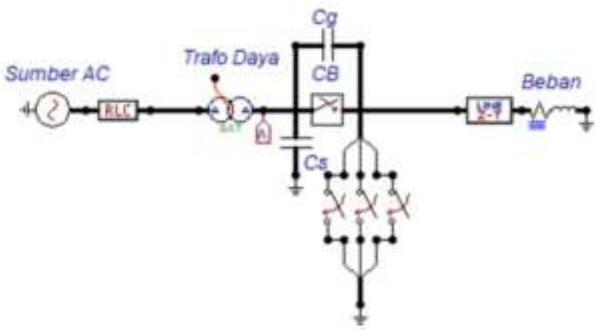

Figure 7. Circuit Modeling with Windings
Power Transformer *Delta-Delta* on Condition *Switching Circuit Breakers*

RESULT

Modeling and Simulation of 20 kV Switching Circuit Breaker with Delta – Wye Power Transformer Winding Connections

In this transient recovery voltage simulation, the peak phase voltage response to ground is proven ($V_{L-N\ peak)}$under normal conditions before the circuit breaker switching occurs as visualized in Figure 8 The value of this voltage is in accordance with the results that should be based on the derivation of the formula in chapter 3. Then a system modeling simulation is carried out when the circuit breaker switching occurs which is visualized in Figure 8.

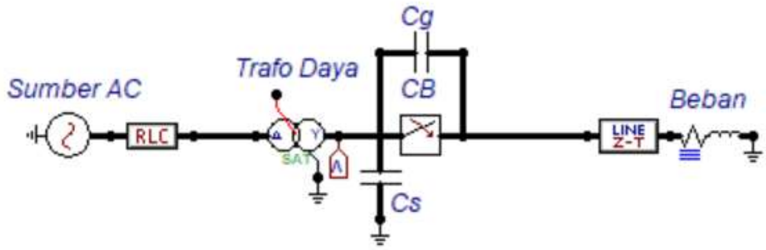

Figure 8. Circuit Modeling with Delta-Wye Power Transformer Windings in Normal

Analysis and Simulation with Delta–Wye Power Transformer Winding Connections when Switching Circuit Breakers

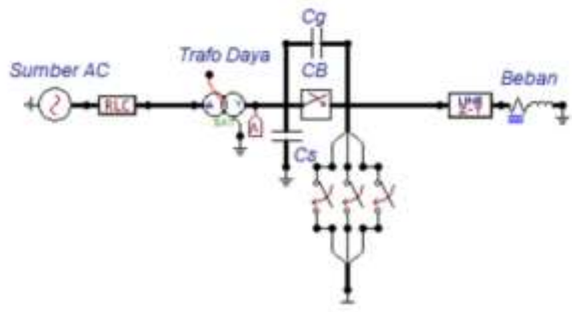

Figure 9. Circuit Modeling with Delta-Wye Power Transformer Windings when Switching Circuit Breakers

The simulation results in ATPDraw show that the peak transient voltage value for the R phase is 37,907.3 V, the S phase is -48,517.6 V and the T phase is 11,831.5 V. Because the system voltage is28,284.27V, then the transient recovery voltage that exceeds the system voltage is in the R and T phases. And the highest transient voltage occurs in the S phase

Table 3. Peak Voltage Transient Recovery Voltage 20 Kv with Transformer Winding Delta-Wye Power

	t (seconds)	(V)
R	0.000142	37,907.3
S	0.000158	-48,517.6
Q	0.000172	11,831.5

Transient Recovery Voltage Analysis with Delta–Wye Power Transformer Winding Connections Using Traveling Waves

Traveling waves that occur in transmission lines are a result of voltage$V_{L-N\ peak}$reflected by the reflection coefficientρAndρ. Transient analysis of traveling waves in calculations uses a lattice diagram, where the surge impedance is large1of 254.23 Ω/m (calculations are shown in sub-chapter 4.1) and the transformer equipment is considered as an open clamp so it has a value of ZL = Z2 = (infinity) while the grounding impedance (Zs) = 0, with The

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peak time for a circuit surge according to IEC standards is 250 μs (0.25 ms).

VL–N peak= 28,284.27

Reflection1, (4.8)
$_1$= (ρ)
=28,284.27 – 0.5213
=-14,744.59 V
Reflection2, (4.9)
$_2$=1(ρ)
=-14744.59 x 1
=-14,744.59 V
Reflection3, (4.10)
$_3$=2(ρ)
=-14744.59 x–0.5213
=7,686.355 V
Sent1,
$_1$=(ρ) (4.11)
=28,284.27 x 0.4787
=13539.68 V
Sent2,
$_2$=2(ρ) (4.12)
=-14,744.59 x 0.4787
=-7,058.235 V
Sent3,
$_3$=4(ρ) (4.13)
=7.686 x 0.4787
=3,679.29 V

This calculation will continue until the traveling wave has a value of 0 V. This will then be completed using a program in MATLAB software by displaying data from the first reflection to the thirtieth reflection.

In transient recovery voltage modeling with the Delta-Wye power transformer winding connection, the percentage value results were obtainedV*transient recovery voltage*toVtraveling wave values are as in Table 4.3. The resulting data states the value ofVtransient recovery voltage in the R phase is 289.20% ofVwaves travel in the same phase. Value ofVtransient *recovery voltage*in the S phase of 267.25% ofVwaves travel in the same phase. Value ofVtransient recovery voltage in the T phase is 189.65% ofVwaves travel in the same phase.

Table 4. Results of Calculation of Traveling Waves in Channels with Delta-Wye Power Transformer Windings

Wave		Wave	
	Bounce		Proceed
	28,284.27	1	13,539.68

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Wave	Bounce	Wave	Proceed
1	-14,744		
	-14,744	2	-70579.5
2			
3	7,686		
	7,686	3	3,679.29
4			
5	-4,007		
	-4,007	4	-1,918.15
6			
7	2,089		
	2,089	5	1,000
8			
9	-1,089		
	-1,089	6	-521.3
10			
11	568		
	568	7	271.9
12			
13	-296		
	-296	8	-141.7
14			
15	154		
	154	9	73.72
16			
17	-80		
	-80	10	-38.3
18			
		41	

Table 5 Results of Calculation of Traveling Waves in Channels with Delta-Wye Power Transformer Windings

Wave Bounce		Wave Proceed	
19	42		
	42	11	20.11
20			
21	-22		
	-22	12	-10.53
22			
23	11		

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Wave Bounce		Wave Proceed	
	11	13	5.27
24			
25	-6		
	-6	14	-2.87
26			
27	3		
	3	15	1.44
28			
29	-2		
	-2	16	-0.957
30			

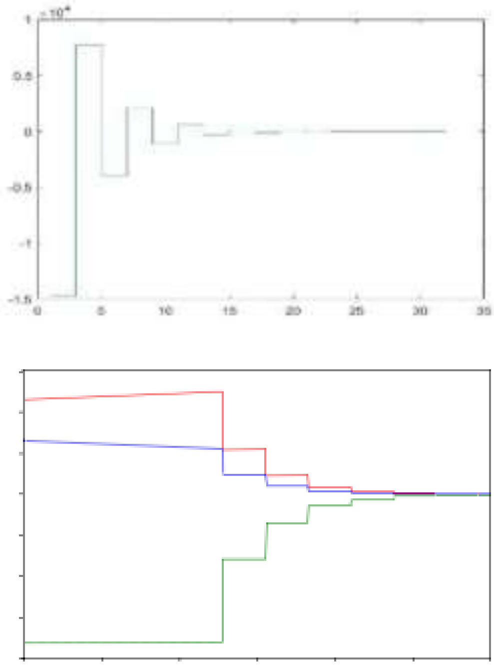

Figure 10. Visualization of Traveling Waves in Medium Voltage Transmission Lines with Delta-Wye Power Transformer Windings

Table 6. Percentage of Transient Recovery Voltage to Traveling Wave

	TRV (V)	Wave Walking (V)	TRV Percentage against Waves walk
R	37,907.3	13,107.5	289.20 %
S	-48,517.6	-18,154.4	267.25 %
Q	11,831.5	6,238.2	189.65 %

In this transient recovery voltage simulation, the peak phase voltage response to ground is proven (VL–N peak)under normal conditions before the circuit breaker switching occurs as visualized in Figure 4.7. The value of the voltage is in accordance with the proper results based on the derivation of the formula in chapter 3. Then a system modeling simulation is carried out when the circuit switching occurs. *breakers*which is visualized by Figure 4.8. Analysis and Simulation with Wye-Delta Power Transformer Winding Connections under Normal Conditions.

CONCLUSION

The following are conclusions based on the results of simulation and analysis of transient recovery voltage using traveling waves in medium voltage switching circuit breakers:

1. Peak voltage value of transient recovery voltage in simulation with four variations of power transformer winding connections, namely:
   a. Delta-Wye = 48,517.6 V
   b. Wye-Delta = 17.547 V
   c. Delta-Delta = 26,801.1 V
   d. Wye-Wye = 17,798.1 V
2. Peak voltage value of the traveling wave in a simulation with four variations of power transformer winding connections, namely:
   a. Delta-Wye = 18,154.4 V
   b. Wye-Delta = 5,023.7 V
   c. Delta-Delta = 8,764.5 V
   d. Wye-Wye = 8,703.3 V
3. The peak voltage value of the transient recovery voltage does not occur in the same phase, namely:
   a. Delta-Wye = S Phase
   b. Wye-Delta = R Phase
   c. Delta-Delta = R Phase
   d. Wye-Wye = S Phase
4. The peak voltage value of the transient recovery voltage is more than 267% of the peak voltage value of the traveling wave in the same phase
5. The peak voltage value of the traveling wave on each phase does not always represent the peak voltage value of the transient recovery voltage on the same phase.
6. The peak voltage value of the transient recovery voltage and traveling wave at each power transformer winding connection varies due to the difference in parameters, namely VL–N, of each power transformer winding connection.

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