Overvoltage Resonance Protection Scheme of 500 kV Extra High Voltage Transmission Lines

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ABSTRACT — Shunt reactors are frequently installed at the end of a 500 kV double circuit extra high voltage transmission lines (EHVTL) to help overcome the voltage rise caused by the long line capacitance. However, voltage problems may still occur, especially during the voltage injection process in new transmission lines that have been installed, due to voltage induction and parameter reinforcement from other circuits within the same line that have been injected earlier. The problem of overvoltage occurrence becomes even more complex because the line and shunt reactor have been completely installed, making it impossible to change the length of the line and the capacity of the shunt reactor. The overvoltage phenomenon in this research occurs when one circuit in the transmission line has not been injected. However, the shunt reactor has been connected so that the line receives induction and strengthening from another circuit because, at the same time, the second circuit has been injected with operating voltage. Overvoltage in this research occurs when one circuit in the transmission line has not been injected. Nevertheless, the shunt reactor has been connected so that the line receives induction and reinforcement from another circuit because, at the same time, the second circuit has been injected with operating voltage. This paper proposes modifications to the voltage injection maneuver scenario into the line, modifications to the protection scheme in the event of a phase-to-ground fault, and the addition of an overvoltage relay to overcome the overvoltage conditions. Modifying the voltage injection maneuver scenario could decrease the overvoltage on lines not injected with voltage up to 31.9 kVp. Changing the protection scheme when a phase-to-ground fault occurred by commanding the shunt reactor's circuit breaker (CB) to open could prevent voltage rises in the undisturbed phase. A voltage relay was added in order to anticipate the occurrence of overvoltage when there was a disturbance in the line, and the shunt reactor CB could not open due to internal disturbances.

KEYWORDS — Shunt Reactor, Double Circuit, Overvoltage, Protection Scheme, Extra High Transmission Line.

I. INTRODUCTION

Overvoltage on extra high voltage transmission lines (EHVTL) is dangerous as it can damage the insulation of connected electrical equipment due to voltage exceeding its capacity [1], [2]. Apart from lightning strikes, overvoltage on EHVTL usually occurs during the switching process. Therefore, it is necessary to anticipate it in order to ensure the stability of electric power distribution [3]–[5]. Shunt reactors are installed at both ends of a 500 kV double circuit EHVTL to counteract the increase in voltage caused by the long-line capacitance [6]–[8]. Installation of shunt reactors on the double circuit EHVTL with long lines to reduce overvoltage problems due to line capacitance is frequently chosen and implemented on both new transmission lines (during construction) and older transmission lines. However, installing a shunt reactor in a double circuit line causes another overvoltage phenomenon at both ends of the line installed with a shunt reactor [9]–[11]. Overvoltage occurs when one of the lines is open and the shunt reactor is in the inlet condition. At the same time, the second line is energized [12]–[14].

Over the past five years, several researchers have studied the occurrence of overvoltage in electrical power distribution systems and have undertaken various endeavors to suppress or reduce it. Of these endeavors is adding the surge arrester equipment and taking control steps on the doubly fed induction generator (DFIG) and point of common coupling (PCC) during grid disturbances [15], [16]. Overvoltage can also be reduced by replacing the disconnector switch (DS) contacts by installing closing resistance on the DS [17]. A three-phase opening scheme in the reactor is applied to mitigate overvoltage resonance [18]–[20]. Lightning protection designs have also

been developed to anticipate overvoltage [21], [22]. Research on overvoltage resonance in transmission lines has resulted in a mechanism to reduce overvoltage due to lightning strikes by conducting steady voltage analysis and simplifying the resonance circuit [23]–[25].

Shunt reactors effectively reduce overvoltage during the loading process or when applying voltage. On the other hand, installing a shunt reactor can increase the induced voltage in non-live lines if the following conditions occur [26].

- In a single circuit line, series resonance will occur when using a single pole auto reclose (SPAR) pattern.
- In a double circuit line, when only one of the lines has voltage, parallel resonance will occur.

Overvoltage resonance occurs when the shunt compensation degree is high. The compensation degree percentage value is determined by comparing the value of the reactor compensation shunt with the positive sequence susceptance of the transmission line [27]. Typically, the compensation degree value falls between the range of 60% to 80% [28].

Previous researchers have provided several alternative solutions to overcome problems when resonance conditions occur in lines [29].

- Makes a complete transposition of the transmission line.
- Create an ungrounding scheme on the reactor neutral line.
- Install a resistor between the ground line and the neutral line of the reactor.
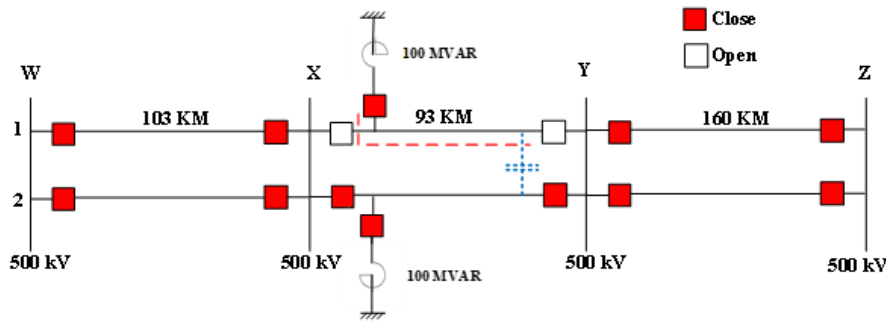- Install a reactor (directly mounted or coupled) between reactor ground and neutral.

Figure 1. Diagram of one transmission line under study when the overvoltage occurs on lines X to Y.

- Replace the disconnecting earth switch (DSE) with a circuit breaker (CB) because the induced voltage at high voltage is dangerous for the DSE because it causes arching between the DSE terminal switches.
- Make changes to the reactor configuration.

This research was carried out to analyze the causes of overvoltage in double circuit lines when one of the lines has been injected with voltage. Then, an overvoltage condition occurs in the non-voltage line when the reactor is inserted into the system. Alternative solutions carried out in this research have never been carried out in previous research, namely as follows.

- Carrying out the process of changing the maneuver scenario when applying voltage, which aims to add line length to prevent overvoltage resonance.
- Changes in the protection scheme design when a single-phase fault occurs as a step to secure the phase, which is not disturbed by the effects of overvoltage resonance.
- Adding an overvoltage relay to the line as an anticipatory step when overvoltage appears due to a disturbance in the line when the reactor CB fails to open.

II. MATERIAL

A. OVERVIEW SISTEM

Figure 1 is a one-line diagram examined when the overvoltage phenomenon occurs. This one-line diagram consisted of four double-circuit transmission lines connecting four 500 kV extra high voltage substations (EHVS): EHVS W, X, Y, and Z. The line length from EHVS W to EHVS X to EHVS Y was 93 km, and the length from EHVS Y to EHVS Z was 160 km. On the X to Y double circuit transmission line, a shunt reactor with a capacity of 100 MVAR with a voltage of 500 kV was installed. The initial condition of CB in EHVS X and EHVS Y was in the open state before injecting voltage to line 1, while line 2 was already in the voltage-injected position.

Tower and conductor geometry data in Figure 2(a) shows a sequence of vertical three-phase conductor bundles, with each phase consisting of four conductor bundles (quadruple). The distance between the lower phase and the ground was 23.49 m, between the middle phase and the ground was 35.89 m, and between the upper phase and the ground was 48.19 m. Figure 2(b) depicts a simplified image of the conductor distance between phases, which simplifies the calculation of the capacitance of a three-phase transmission line.

B. THE PROCESS OF OCCURRING OVERVOLTAGE DURING THE VOLTAGE PROCESSING PROCESS

Figure 1 depicts the occurrence of overvoltage when the dual line 500 kV EHVTL is being energized from EHVS X to
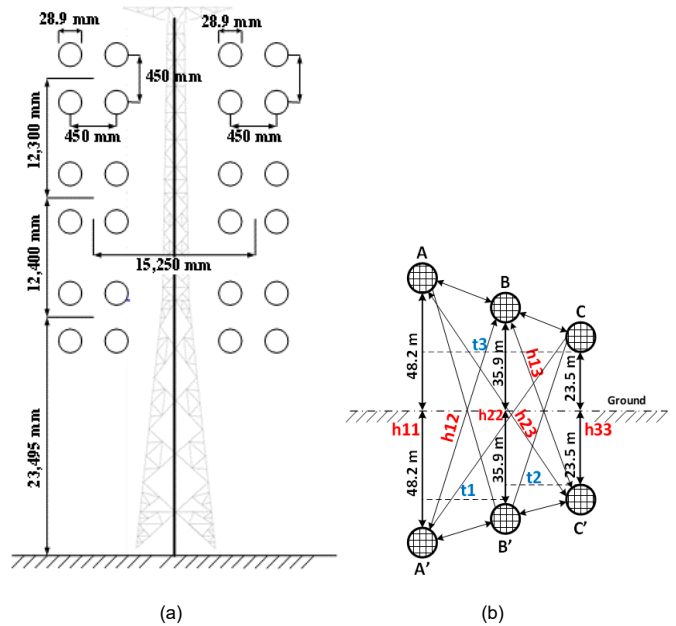

Figure 2. Images of (a) tower geometry, (b) simplification of line capacitance.

EHVS Y. The voltage in line 1 exceeded the standard operating limit and rose to 584.93 kV when the shunt reactor CB was inserted, despite line 1 was not yet live. Line 2 was already live with the shunt reactor CB entering the system. The event of a voltage rises above the standard operating limit also occurred in line 2 when the shunt reactor CB in line 2 was inserted, despite line 2 was not yet live. At the same time, line 1 was already experiencing a voltage drop, with the shunt reactor CB being introduced into the system.

Figure 3 depicts the recording of the digital fault recorder (DFR). Figure 3(a) shows that the overvoltage on line 1, which did not receive any voltage injection, was measured at 584.93 kVp. Meanwhile, line 2 was in a voltage-injected state.

Figure 3(b) shows the occurrence of overvoltage on a line that had not been injected with voltage (line 2) of 584.93 kVp. Meanwhile, the following line (line 1) was in a voltage-injected condition.

III. METHODOLOGY

In this research, measurements, and analysis to determine the overvoltage value were carried out using the following steps. The first step was to carry out a line capacitance calculation analysis. Equation (1) is a calculation of the compensation degree value (k).

$$k = \frac{B_L}{B_C} = \frac{\frac{1}{(\omega.L)}}{(\omega.C_+)} = \frac{1}{\omega^2.L.(C_{pg}+3.C_{pp})} \qquad (1)$$
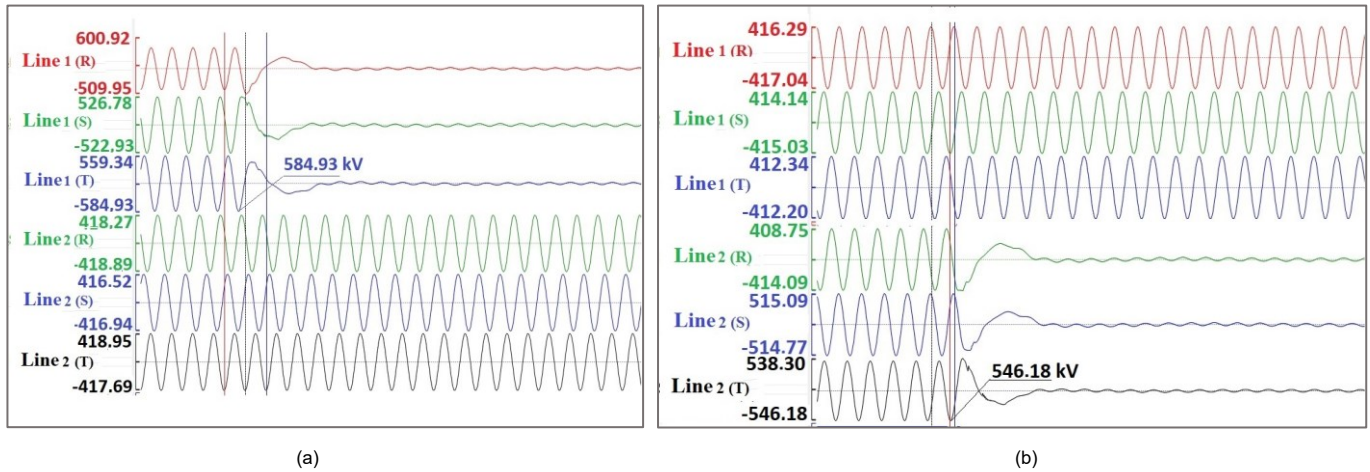
(a)

(b)

Figure 3. DFR recording, (a) line 1 in the absence of any voltage injection and (b) line 2 in the absence of any voltage injection.

where C_+ is the positive sequence capacitance, C_{pg} is the line capacitance to ground, C_{pp} is the interphase line capacitance in units of F/m, and L is the inductance in H unit. Meanwhile, the transmission line capacitance value can be obtained using (2) and (3).

$$C_{pg} = \frac{2\pi\varepsilon_0}{{}^e log\left[\frac{D_{eq}}{r}\right] - {}^e log\left[\frac{D_{AB'}D_{BC'}D_{CA'}}{D_{AA'}D_{BB'}D_{CC'}}\right]^{\frac{1}{3}}} \quad (2)$$

$$C_{pp} = \frac{C_{pg}}{2} \quad (3)$$

where D_{eq} is the subconductor distance, $D_{AB'}D_{BC'}D_{CA'}$ are the interphase conductor distance, and r is the bundle conductor radius. Based on (1) and Figure 2(b), the line-to-ground capacitance value (C_{pg}) and the anaphase capacitance value (C_{pp}) were calculated, resulting in the following results.

$$C_{pg} = \frac{2x3.14x8.85x10^{-12}}{{}^e log\left[\frac{0.045}{0.0109}\right] - {}^e log\left[\frac{118.94x84x101.4}{96.4x71.8x47}\right]^{\frac{1}{3}}} = 1.66x10^{-11} F/m$$

$$C_{pp} = \frac{C_N}{2} = 0.83x10^{-11} \ F/m.$$

From the results of the calculations above, the phase-to-ground line capacitance value was $1.66x10^{-11}F/m$, and the interphase line capacitance was $0.83x10^{-11} \ F/m$, which was an X to Y transmission line with length of 93 km. After obtaining the line capacitance value, the shunt compensation degree (k) value was calculated, resulting in the following results.

$$k = \frac{1}{\omega^2.L.(C_{pg} + 3.C_{pp})}$$

$$k = \frac{1}{(2\times3.14\times50)^2\times2,64\times(1.66+3x0.83)\times10^{-11}\times93000}$$

$$k = 0.9942 = 99.42\%.$$

The shunt compensation degree (k) value obtained was 99.42% following the injection of shunt reactor data and line capacitance values. Figure 4 shows that the value (k) of the line being examined reached its peak of overvoltage resonance when the shunt compensation degree (k) value was shifted from 10% to 200%. It could potentially cause overvoltage resonance in the line.

The second step was to model the 500 kV tower configuration and inter-circuit and inter-phase couplings of the $W - X - Y - Z$ transmission line in DIgSILENT Power Factory
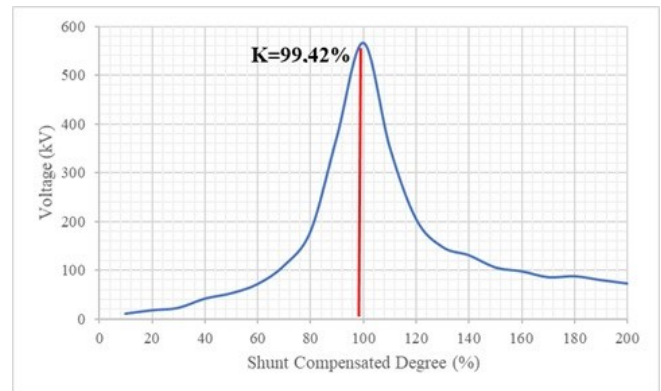

Figure 4. Shunt compensation degree graph on the X to Z line with a change in the k value from 10% to 200%.

software based on field data. Then, the third step involved validating the simulation model against recorded data of disturbances that occurred when line 1 experienced an overvoltage, when line 2 was injected with voltage and the reactor entered the system. A validation comparison of DFR recordings with simulation results showed identical results. From the observations on the DFR, the induced voltage was 25.36 kVp. Meanwhile the simulated induced voltage was 28.6 kVp prior to the installation of CB reactor line 1. Furthermore, after the reactor CB was closed, the simulated voltage on line 1 was 583.57 kVp. It was aligned with the DFR recording for line 1,584 kVp.

The fourth step involved validating the simulation model against recorded data of disturbances that occurred when line 2 experienced an overvoltage, when line 1 was injected with voltage and the reactor entered the system. The validation of the DFR recordings was compared with the simulation results and yielded identical results. From the observations on the DFR, the induced voltage was 25.03 kVp. Meanwhile the simulated induced voltage was 28.6 kVp prior to the installation of CB reactor line 2. Furthermore, after the reactor CB was closed, the simulated voltage in line 2 was 546.46 kVp. This result was aligned with the DFR recording in line 2, which was 546 kVp in line 2, even after the reactor CB was closed.

The fifth step involved simulating and analyzing the voltage profile after changing the maneuver scenario when injecting voltage to the transmission line. Then, the sixth step was to conduct a simulation and analysis of the voltage profile after changing the protection scheme design by changing the reactor CB open command design during a single-phase fault.
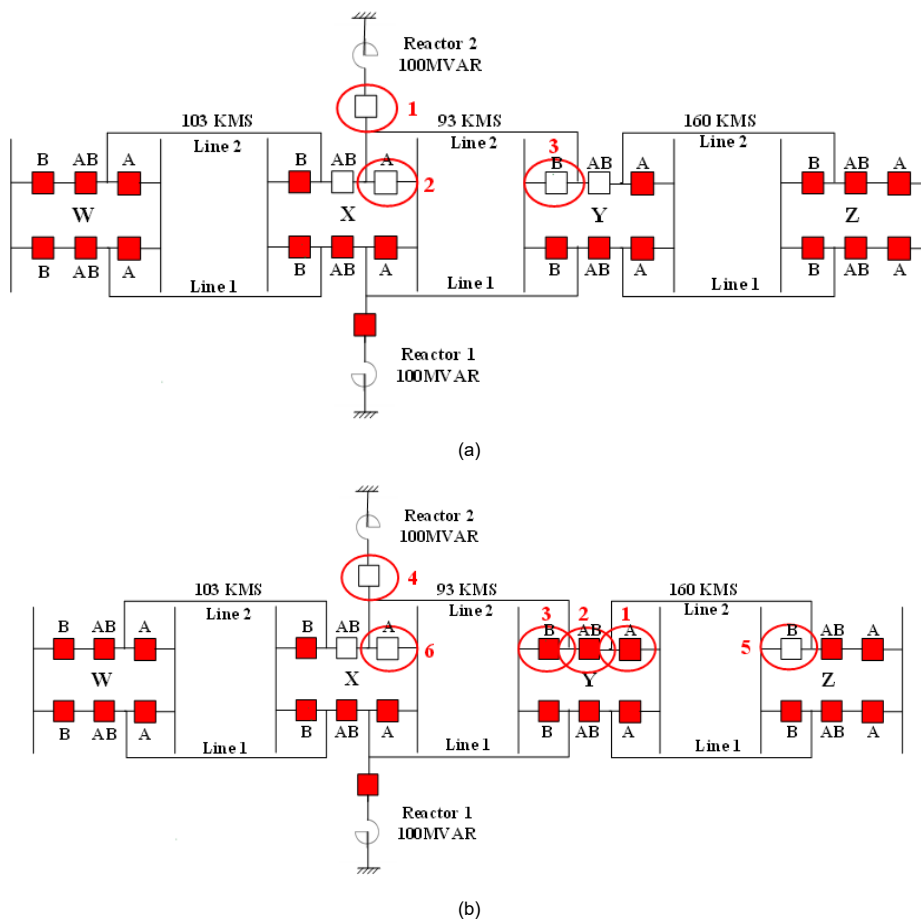
(a)

(b)

Figure 5. Single-line diagram of, (a) process of applying tension according to the initial SOP, (b) changes in the sequence of maneuvers in the process of injecting voltage.

The seventh step was to simulate and analyze the voltage profile after adding an overvoltage relay (OVR) to the transmission line. The eighth stage involved simulating a load in order to observe the stress profile under minimum load, maximum load, gradual load increase, and load release from maximum to minimum. The loading simulation was carried out using an inter-bus transformer (IBT) installed on EHVS, with the following data.

- At EHVS W, there were two IBTs with a capacity of 500 MVA per transformer.
- At EHVS Y, there were two IBTs with a capacity of 500 MVA per transformer.
- At EHVS Z, there were two IBTs with a capacity of 500 MVA per transformer.

The results of steps five to eight will be discussed in subsections IV. A to IV. D.

IV. RESEARCH RESULTS

This section discusses the simulation results from steps five to eight in anticipating and overcoming overvoltage on the line.

A. MAKING MANUVER SCENARIO CHANGES DURING THE VOLTAGE PROCESSING PROCESS

Changes in line impedance values can be done by extending the transmission line, namely by reconfiguring the sequence of voltage supply maneuvers, as explained in Figure 5.

Figure 5(a) is a one-line diagram of the sequence of maneuvers according to the initial standard operating procedure (SOP) for the injection of voltage. In contrast, Figure 5(b) shows a one-line diagram of changes in the voltage injection maneuver. The sequence of voltage injection maneuvers is described in the flowchart in Figure 6.

Figure 6 shows that the initial scenario was conducted by positioning CB A and AB in EHVS X and EHVS Y in the open position. Next, the first process was carried out by closing the reactor CB in the line. Then, in the second and third processes, CB A in EHVS X and CB B in EHVS Y were closed [30]. When the CB reactor was closed, the line experienced overvoltage, despite the absence of any voltage injection. In order to anticipate this, changes were then made to the maneuver scenario when injecting voltage, with the first process being inserting CB A, followed by CB AB and CB B in EHVS Y. Once all CBs in EHVS Y were inserted, the second line reactor CB was subsequently inserted. Afterwards, CB A in EHVS X and CB B in EHVS Z were inserted sequentially.

Changes to the maneuver caused the capacitance value that influenced the induced voltage to increase to 253 km, namely the transmission line from EHVS X-Y-Z. According to the length of the line from EHVS X to Y, initially, the capacitance value that influences the induced voltage is 93 km. Increasing the length of the line will affect the value of the shunt compensation degree (k). The following results were obtained after carrying out calculations based on (2).

$$k = \frac{1}{\omega^2 . L . (C_{pg} + 3 . C_{pp})}$$

$$k = \frac{1}{(2 \times 3.14 \times 50)^2 \times \frac{7.93}{3} \times (1.66 + 3 x 0.83) \times 10^{-11} \times 253000}$$

$$k = 0.3654 = 36.54\%.$$

The shunt compensation degree (k) of 36.54% had no potential to cause overvoltage after proving it by simulating changes to the maneuver scenario in the DIgSILENT Power
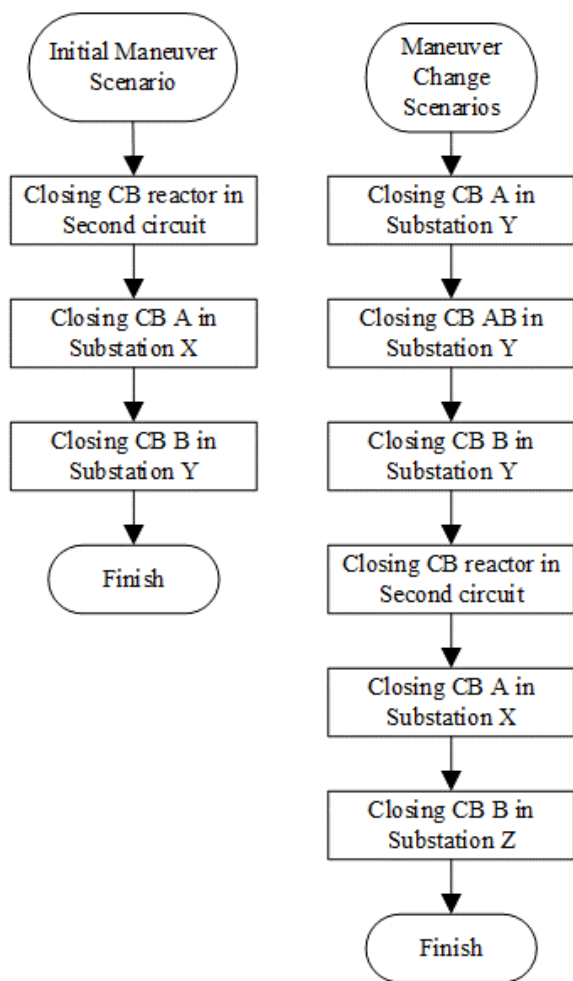
Figure 6. Flowchart of the sequence of voltage injection maneuver according to the initial SOP and after changes.

Figure 7. Simulation results of changes in maneuver scenarios during the tensioning process.

Factory software. Figure 7 is a voltage profile resulting from a simulation of changes in voltage maneuvers showing that there was no overvoltage in the line. The voltage in the line was measured at 31.928 kVp after being inserted into the CB reactor at 0.1 s.

B. CHANGE IN PROTECTION SCHEME DESIGN DURING 1 PHASE DISTURBANCE

In the initial design, the CB reactor scheme will open when the transmission line receives an open command from the five inputs inputted in the OR gate. The five inputs are:

- circulating current protection (CCP) relay,
- three-phase faults on the line,
- circuit breaker failure (CBF) relay A,
- circuit breaker failure (CBF) relay B, and
- overvoltage relay (OVR).

From this initial design, when a single-phase disturbance occurs, the safety relay does not command the reactor CB to open, thereby affecting the voltage on the uninterrupted phase. It happens because the line capacitance value in the disturbed phase can result in resonance if the end of the line is still connected to the shunt reactor [31].

To account for this condition, the reactor CB opening scheme was modified by adding a single-phase line disturbance as one of the conditions for opening the reactor CB during a disturbance. When a single-phase disturbance occurs, the conditions for opening the reactor CB consist of six inputs entering a single OR gate:
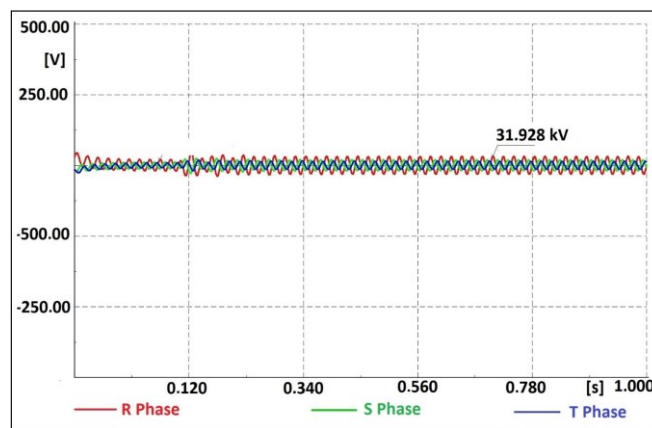
- CCP relay,
- single-phase fault on the line,
- three-phase faults on the line,
- CBF A relay,
- CBF B relay, and
- OVR relay.

The reactor CB will open if it receives one of the six interference signals. To determine the voltage profile in the undisturbed phase when a single-phase disturbance occurs, a simulation was carried out by adding a disturbance in the R phase. Figure 8(a) shows the simulation results during a single-phase disturbance in the R phase. The S and T phases that were not disturbed experiencing voltage rise of 575.79 kVp and 537.8 kVp, respectively.

Figure 8(b) is the simulation result after changes to the protection design. The figure shows no voltage rise in the undisturbed phases, namely phase S and phase T, with voltage values of 424 kVp and 426 kVp. The voltage in the S phase and T phase was back to normal after the parallel circuit between the reactor and the line causing the overvoltage resonance was disconnected by opening the reactor CB.

C. ADDITION OF OVR TO THE NETWORK

To anticipate the occurrence of overvoltage once the line can operate and the double circuit is injected with voltage, it is necessary to install an OVR with two schemes. First, OVR basic was utilized as protection against line overvoltage with the following three output signal commands:

- open the CB reactor,
- open CB lines, and
- sends a direct transfer trip (DTT) signal to the opposing EHVS.

The second scheme was the OVR resonance. This scheme was created to anticipate overvoltage when one or three-phase disturbances occurred. However, the reactor CB failed to open due to internal problems, such as mechanical damage or problems with the circuit. The second OVR logic scheme had two delay time stages with different targets to open the CB, namely as follows.

- The first stage of delay time had a duration of 2 s with an output signal commanding to open the reactor CB again.
- The second stage of two delay time had an additional time duration of 3 s. This second stage occurred if the reactor CB had not opened when commanded to open
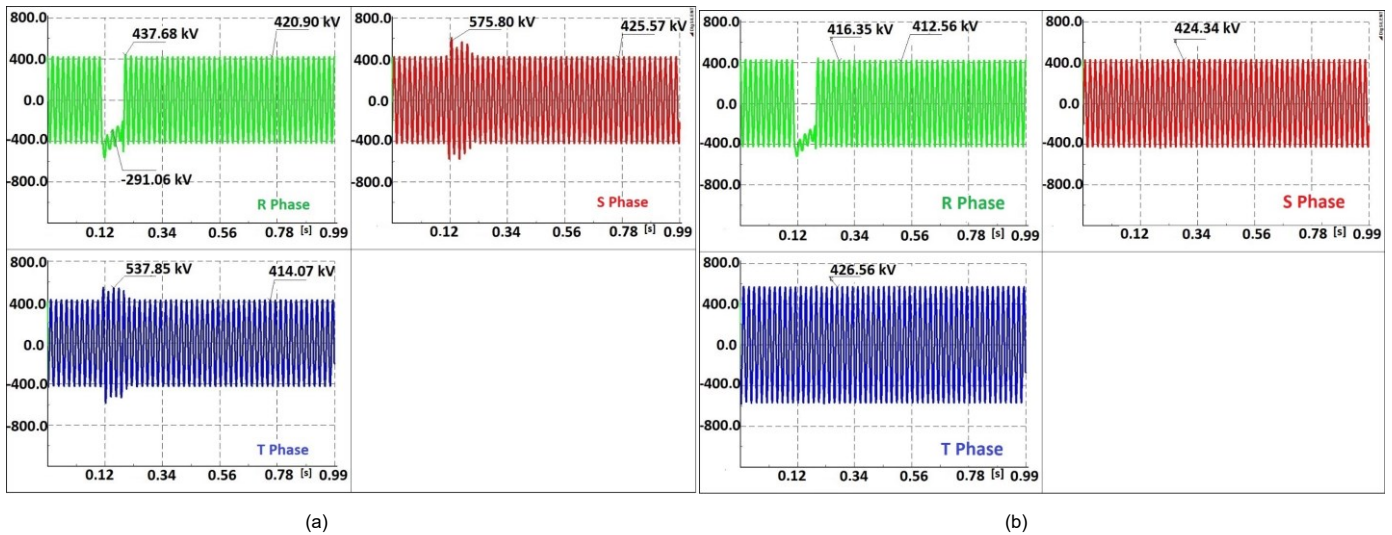
(a)   (b)

Figure 8. Voltage profile when a single-phase fault occurs, (a) with the reactor CB still in, (b) with the reactor CB already opened.

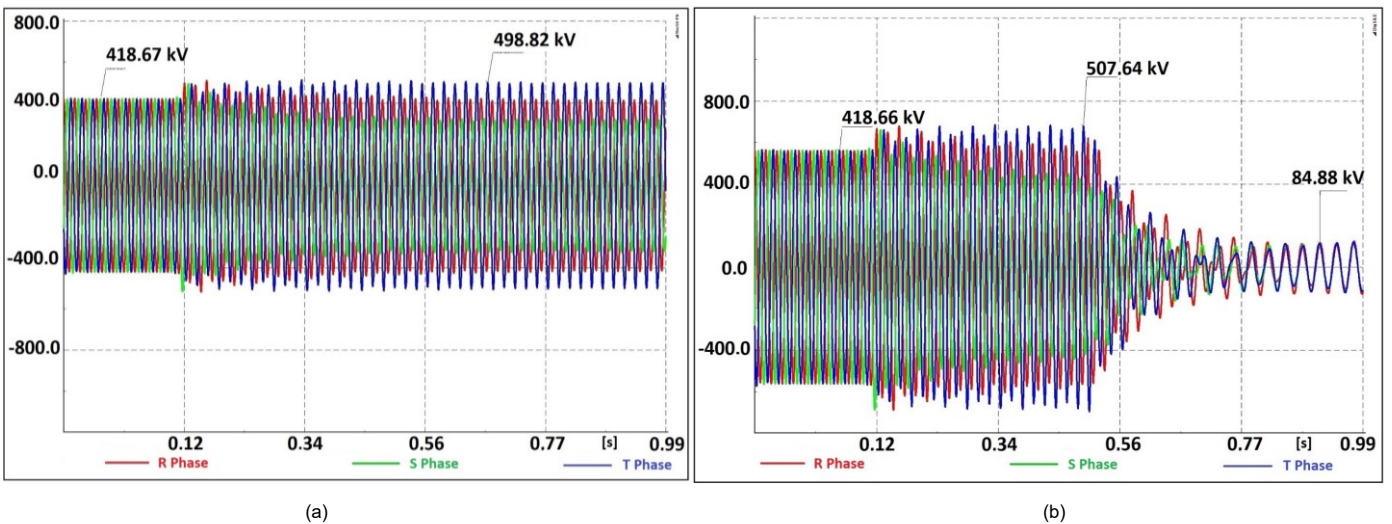(a)   (b)

Figure 9. Voltage profile, (a) when a line fault occurs, and the reactor CB remains in, (b) after applying OVR resonance by opening the next CB.

the stage one. The output signal would open the line CB and the CB reactor of the adjacent line to eliminate excess voltage due to the influence of induction in the adjacent line.

Figure 9(a) shows the results of observing the voltage profile when a disturbance occurs in the line, but the reactor CB remains closed. The voltage rose to 498.8 kVp, even though the CB line was in the open position. The simulation results of applying OVR resonance can be seen in Figure 9 (b), which shows that the voltage drops to 84.87 kVp after the CB line next to it is opened. The cause of the voltage drop was the induction into the parallel circuit of the reactor, which failed to open with the disturbed line having been eliminated when the adjacent line's CB was opened.

D. SIMULATION OF LOADING ON THE LINE

Following the operation of the X to Y transmission lines and the injection of voltage into the double circuit, a load simulation was carried out on the line using several simulations as follows.

- Maximum load of 100%, which was equivalent to 3,000 MVA. It is done by including all IBTs on lines W through Z.
- Minimum load of 0%, without including IBT on lines W to Z.

- Increasing the load gradually in the range of 14% to 17%, equivalent to 410 MVA to 520 MVA.
- Loading shedding from a maximum load of 100% to a minimum load of 0% so that in this condition, the IBT was released from the system.

From these four simulations, voltage observations were then carried out on line 1 and line 2, which was during the switching process and at a steady state. Observations were conducted during the switching process to see the transient voltage that arises.

The process of injecting and removing loads often results in momentary overvoltage. Therefore, steady voltage observations were carried out to observe and ensure that there was no overvoltage for a long time in the line after the loading process was carried out. The line loading simulation results are shown in Table I and Table II.

According to Table I and Table II, the switching voltage during the highest line loading process was 1,1 p.u or equivalent to 550 kV. This voltage of 1,1 p.u is still safe and does not damage installed equipment such as CB, current transformer (CT), DS, and lightning arrester (LA) as this equipment can withstand switching voltages of up to 1,175 kV, according to the technical data of the installed equipment.

Under 100% maximum load conditions, a voltage dropped of up to 0.982 p.u or the equivalent of 491 kV. This voltage

TABLE I
SWITCHING VOLTAGE PROFILE DURING LOADING

Line	Switching Voltage During Loading (p.u)						
	100%	*83%*	*66%*	*50%*	*33%*	*16%*	*0%*
Line 1	0.982	1.057	1.106	1.116	1.143	1.075	1.074
Line 2	0.987	1.061	1.111	1.112	1.131	1.075	1.074

TABLE II
STEADY VOLTAGE PROFILE DURING LOADING

Line	Steady Voltage During Loading (p.u)						
	100%	*83%*	*66%*	*50%*	*33%*	*16%*	*0%*
Line 1	0.982	1.012	1.032	1.048	1.060	1.060	1.061
Line 2	0.982	1.019	1.040	1.052	1.060	1.060	1.060

TABLE III
VOLTAGE PROFILE DURING LOAD REMOVAL

Line	Switching Voltage During Load Removal (p.u)
Line 1	1.437
Line 2	1.417

drop is still within safe limits according to the 2020 electric power system network regulations/grid code, namely the voltage rise limit is +5% or 525 kV and the voltage drop is -5% or 475 kV. The highest steady voltage was 1.06 p.u or equivalent to 530 kV. It occurred at load conditions of 0% to 33% or 0 MVA to 990 MVA. This voltage exceeds the 5% voltage rise limit. The lowest steady voltage was 0.982 p.u or the equivalent of 491 kV, occurred when the maximum load is 100% or 3,000 MVA. This lowest steady-state voltage condition is still within the standard grid code limit, namely -5% [32]. Table III shows the switching voltage during load shedding from 100% or 3,000 MVA to 0%, with the condition that is no IBT connected to lines W to Z.

The switching voltage on line 1 was 1.437 p.u or equivalent to 718.5 kV, while the switching voltage on line 2 was 1.417 p.u or equivalent to 708.5 kV. The switching voltage measured at the time of load removal is still within the safe limits of the equipment because the installed equipment can withstand switching voltages of up to 1,175 kV.

V. CONCLUSION

Based on the simulation results of the efforts made to reduce the overvoltage on the X-Y line, it can be concluded that the cause of the occurrence of an overvoltage resonance in the line that has not been injected with voltage on the double circuit line when line 2 already energized was the value of the shunt compensation degree (k) reaching 99.42%. It was obtained from the installed reactor capacity value of 100 MVAR and a line length of 93 km. The step to reduce the overvoltage was to change the scenario during the voltage application process, namely by first inserting CB A, AB, and B into EHVS Y to extend the line to 253 km so that the shunt compensation degree (k) value became 36.54. The measured voltage value became 31.9 kVp after the CB reactor closing process. When the double circuit operates, it is necessary to add a SPAR scheme as a condition for opening the reactor CB to anticipate voltage rises in the undisturbed phase. After simulations, it was proven that this process could reduce the voltage rise in the undisturbed phase. The addition of the OVR relay was done in anticipation when there was an overvoltage on the line, but the reactor CB could not open due to internal interference. This process was conducted using a scheme to command open the CB of the next

line, which was successfully simulated and reduced the voltage to 84.87 kVp.

The load simulation on the line showed that the steady voltage remained above the safe limit of +5% when the load was below 990 MVA. Whereas, when the load was increased to a maximum of 3,000 MVA, the voltage drop remained within the standard, namely less than-5%. While increasing the load gradually and when releasing the load, the switching voltage was still within the safe limits of the equipment's ability to withstand the switching voltage.

CONFLICT OF INTEREST

The author of the paper, "Overvoltage Resonance Protection Scheme of 500 kV Extra High Voltage Transmission Lines," declares that this paper is free from conflicts of interest.

AUTHOR CONTRIBUTION

Conceptualization, Imam Ghozali, Mochammad Facta, and Abdul Syakur; software, Imam Ghozali; validation, Mochammad Facta and Abdul Syakur; formal analysis, Imam Ghozali, Mochammad Facta, and Abdul Syakur; source, Imam Ghozali; writing–original draft preparation, Imam Ghozali; writing–review and editing, Imam Ghozali, Mochammad Facta, and Abdul Syakur.

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REFERENCES

[1] A.P. Singh, S. Ghosh, A.S. Rones V., and S. Sahay, "Analysis and Mitigation of Secondary Arcing & Resonance Overvoltage Problem in Shunt Compensated Lines -Case Study," *2022 IEEE IAS Glob. Conf. Emerg. Technol. (GlobConET)*, 2022, pp. 140–145, doi: 10.1109/GlobConET53749.2022.9872373.

[2] R.M.A. Velásquez and J.V.M. Lara, "The Problem of the Actual Insulation Coordination for 500 kV with Overvoltage in Substations and the Needed for More Surge Arresters in High Voltage Grid," *Ain Shams Eng. J.*, Vol. 4, No. 9, pp. 1–15, Sep. 2023, doi: 10.1016/j.asej.2023.102130.

[3] Y.L. Xin *et al*., "Configuration of Suppression Schemes Against High-Frequency Transient Reignition Overvoltages Caused by Shunt Reactor Switching-Off in Offshore Wind Farms," *Int. J. Elect. Power, Energy Syst.*, Vol. 141, pp. 1–10, Oct. 2022, doi: 10.1016/j.ijepes.2022.108170.

[4] H. Ren, "Analysis on Switching Overvoltage of 500 kV GIS Disconnector," *Energy Reports*, Vol. 8, pp. 169–176, Aug. 2022, doi: 10.1016/j.egyr.2022.02.143.

[5] S. Grebovic, N. Oprasic, and A. Balota, "Influence of Shunt Reactor Switching on Overvoltages in 400 kV Substation," *2020 9th Mediterr. Conf. Embed. Comput. (MECO)*, 2020, pp. 1–4, doi: 10.1109/MECO49872.2020.9134116.

[6] N. Pfeifer, M. Kizilcay, and P. Malicki, "Analytical and Numerical Study of an Iron-Core Shunt-Compensation Reactor on a Mixed Transmission Line," *Elect. Power Syst. Res.*, Vol. 220, pp. 1–8, Jul. 2023, doi: 10.1016/j.epsr.2023.109315.

[7] A. Župan, B. Filipović-Grčić, and D. Filipović-Grčić, "Transients Caused by Switching of 420kV Three-Phase Variable Shunt Reactor," *Elect. Power Syst. Res.*, Vol. 138, pp. 50–57, Sep. 2016, doi: 10.1016/j.epsr.2015.12.010.

[8] J. Hu, P. Yuan, X. Li, and Y. Liu, "Analysis on the Necessity of High-Voltage Shunt Reactors in Power Grid," *2020 10th Int. Conf. Power, Energy Syst. (ICPES)*, 2020, pp. 83–87, doi: 10.1109/ICPES51309.2020.9349640.

[9] V. Yari, S.H. Khalaj, and F. Ghelichi, "A Study on Reclosing of Asaluyeh-Isfahan 765 kV Transmission Line Considering the Effect of Neutral Reactor in Reducing Resonant Voltages," *2012 Asia-Pac. Power, Energy Eng. Conf.*, 2012, pp. 1–5, doi: 10.1109/APPEEC.2012.6307333.

[10] Y. Wang and X. Wang, "Influence of Combined Protective Circuit Parameters on Protective Effect of Breaking Overvoltage for Shunt

Reactor," *2018 12th IEEE Int. Conf. Prop., Appl. Dielect. Mater. (ICPADM)*, 2018, pp. 852–855, doi: 10.1109/ICPADM.2018.8401162.

[11] M.H. Samimi *et al*., "Reactor Failure due to Resonance in Zahedan-Iranshahr Parallel EHV Lines, Analysis and Practical Solutions," *Acta Polytech. Hung.*, Vol. 11, No. 1, pp. 63–78, Jul. 2014, doi: 10.12700/APH.11.01.2014.01.5.

[12] M. Pickett, H. Manning, and H.V. Geem, "Near Resonant Coupling on EHV Circuits: I - Field Investigations," *IEEE Trans. Power Appar., Syst.*, Vol. PAS-87, No. 2, pp. 322–325, Feb. 1968, doi: 10.1109/TPAS.1968.292025.

[13] M. Hesse and D. Wilson, "Near Resonant Coupling on EHV Circuits: II - Methods of Analysis," *IEEE Trans. Power Appar., Syst.*, Vol. PAS-87, No. 2, pp. 326–334, Feb. 1968, doi: 10.1109/TPAS.1968.292026.

[14] K. Priest, A. Ramirez, H. Nowak, and J. LaForest, "Resonant Voltages Reactor Compensated Extra-High-Voltage Lines," *IEEE Trans. Power Appar., Syst.*, Vol. PAS-91, No. 6, pp. 2528–2536, Nov. 1972, doi: 10.1109/TPAS.1972.293432.

[15] X. Liu, P. Zhang, X. Deng, and D. Sun, "Hierarchical Overvoltage Predictive Control Scheme for a DFIG-Based Wind Farm," *Elect. Power Syst. Res.*, Vol. 217, pp. 1–19, Apr. 2023, doi: 10.1016/j.epsr.2023.109172.

[16] Y. Li, Y. Zeng, W. Zhang, and C. Qin, "Coordinated Optimization Method for Suppressing Transient Overvoltage Caused by HVDC Commutation Failure Considering Large Wind Power Integration," *Energy Rep.*, Vol. 9, pp. 1171–1182, Dec. 2023, doi: 10.1016/j.egyr.2022.12.037.

[17] J. Santiago and M.C. Tavares, "Relevant Factors for Temporary Overvoltages due to Fault-Resonance Conditions on Half-Wavelength Transmission Lines," *Elect. Power Syst. Res.*, Vol. 175, pp. 1–12, Oct. 2019, doi: 10.1016/j.epsr.2019.105886.

[18] E. Nashawati, N. Fischer, B. Le, and D.I. Taylor, "Impacts of Shunt Reactors on Transmission Line Protection," presented at 38th Annu. West. Prot. Relay Conf., Spokane, WA, USA, 18–20 Oct. 2011.

[19] F. Iliceto, E. Cinieri, and A. Vita, "Overvoltages Due to Open-Phase Occurrence in Reactor Compensated EHV Lines," *IEEE Trans. Power Appar., Syst.*, Vol. PAS-103, No. 3, pp. 474–482, Mar. 1984, doi: 10.1109/TPAS.1984.318725.

[20] X. Lei *et al*., "Research on Resonance Overvoltage of EHV Transmission Lines Caused by Lightning Strike," *IEEE Access*, Vol. 9, pp. 123777–123785, Sep. 2021, doi: 10.1109/ACCESS.2021.3109597.

[21] X. Xiao and W. Lu, "Simulation Analysis on Lightning Overvoltage of 500kV Substation," *16th IET Int. Conf. AC, DC Power Trans. (ACDC 2020)*, 2020, pp. 1668–1672, doi: 10.1049/icp.2020.0189.

[22] C. Jaipradidtham, "Probability Parameter Estimation of Outage Rate Effects for Lightning Overvoltage Analysis on 500 kV EHV Double Circuit Transmission Lines Using Neural Networks," *2005 Int. Power Eng. Conf.*, Vol. 2, 2005, pp. 803–808, doi: 10.1109/IPEC.2005.207018.

[23] T. Lin *et al*., "Analysis of Effect of System Configuration and Parameters on Energization Overvoltage in 330kV Hybrid OHL-Cable System," *2020 IEEE Int. Conf. on High Volt. Eng., Appl. (ICHVE)*, 2020, pp. 1–4, doi: 10.1109/ICHVE49031.2020.9279731.

[24] X. Gu *et al.*, "The Simulation of the Controllable Reactor and It's Application in Ultra High Voltage Transmission Lines," *2011 Int. Conf. Adv. Power Syst. Automat., Prot.*, 2011, pp. 1833–1837, doi: 10.1109/APAP.2011.6180664.

[25] V. Kuchanskyy, "Application of Controlled Shunt Reactors for Suppression Abnormal Resonance Overvoltages in Assymetric Modes," *2019 IEEE 6th Int. Conf. Energy Smart Syst. (ESS)*, 2019, pp. 122–125, doi: 10.1109/ESS.2019.8764196.

[26] M.V. Escudero and M. Redfern, "Effects of Transmission Line Construction on Resonance in Shunt Compensated EHV lines," presented at Int. Conf. Power Syst. Transients (IPST'05), Montreal, Québec, Kanada, 19–23 Jun. 2005, Paper IPST05 – 109.

[27] W. Reid, R. Gustin, and P. Zylstra, "Guidelines for Determining Parallel Resonance on EHV Transmission Lines," *IEEE Trans. Power Appar., Syst.*, Vol. PAS-102, No. 9, pp. 3196–3204, Sep. 1983, doi: 10.1109/TPAS.1983.318129.

[28] J.R. Marti, "Accurate Modelling of Frequency-Dependent Transmission Lines in Electromagnetic Transient Simulations," *IEEE Trans. Power Appar., Syst.*, Vol. PAS-101, No. 1, pp. 147–157, Jan. 1982, doi: 10.1109/TPAS.1982.317332.

[29] M.H. Samimi, I. Ahmadi-Joneidi, A. Majzoobi, and S. Golshannavaz, "Appropriate Selection of Shunt Compensation Reactor in Parallel Transmission Lines: A Case Study," *Int. J. Elect. Power, Energy Syst.*, Vol. 96, pp. 163–173, Mar. 2018, doi: 10.1016/j.ijepes.2017.09.041.

[30] SOP Energize GITET 500 kV Indramayu, Vol. 072/PR/P2B-OPS-DLP, PT PLN UIP2B Jawa, Depok, Indonesia, 2021.

[31] *Control and Schematic GITET PLTU Indramayu 500 kV*, ABB Sakti Industri, Jakarta, Indonesia, 2021.

[32] "Aturan Jaringan Sistem Tenaga Listrik (Grid Code)," Regulation of the Minister of Energy and Mineral Resources of the Republic of Indonesia, No. 20, 2020.