Distribution Substation and SVR Models for Electromagnetic Transient Simulations of Distribution Systems

Nagashima Tomohiro, Taku Noda, and Itaru Watanabe

Abstract—**Conventionally, the voltage regulation of a distribution line in Japan has been carried out by the load ratio control transformer (LRT) of a main transformer in the substation from which the distribution line is sent out. If the distribution line is long and its voltage drop is excessive, one or more step voltage regulators (SVRs) are inserted on the way of the distribution line also for regulating the voltage along it. Due to the wide spread of photovoltaic (PV) generation systems in recent years, the PV generation systems now come to affect the conventional voltage regulation devices mentioned above. Since the control systems of the PV generation systems are not coordinated with those of the conventional voltage regulation devices, their inference is of a great concern. Protective relay coordination of those devices is also important. In order to investigate these problems, electromagnetic transient (EMT) simulations which give detailed three-phase waveforms of voltages and currents are required. To this end, EMT simulation models of distribution substations and SVRs have been developed and used for studies of interference between conventional voltage regulation devices and PV generation systems. This paper presents the developed models and the results of a study.**

Keywords: **electromagnetic transient simulations, distribution systems, distribution substation, and step voltage regulator.**

I. Introduction

DUE to the Great East Japan Earthquake in 2011, interest in renewable energy has been increasing in Japan. To promote renewable energy and to reduce non-renewable fuel consumption, the Japanese government has enforced a Feed-In Tariff (FIT) law in 2012. Since its enforcement, the total capacity of renewable energy power sources interconnected to the power system has exceeded 9 GW by the end of March 2013, and 97 percent of them are photovoltaic (PV) generation systems. Furthermore, most of them are connected to distribution systems. Power generated by those PVs is injected into distribution systems via power conditioning systems (PCSs). PCSs are so-called power electronics converters composed of semiconductor switching devices, and they can perform high-speed control in the order of milliseconds to seconds. In Japan, the voltage of a distribution line has been regulated basically by a Load Ratio control Transformer (LRT) of a main transformer in the substation from which the distribution line is sent out. The LRT is a tap changer for regulating the sending-out voltage. When the distribution line is long and its voltage drop is heavy, a Step Voltage Regulator (SVR), which is a step-up autotransformer with an on-load tap changer (LTC), is inserted in the middle of the line so as to step up and control the voltage. When the line is even longer and one SVR is not enough, more than two SVRs are installed. These conventional voltage regulation devices, LRT and SVR, perform voltage regulation in the order of seconds to tens of seconds. Since the control systems of PCSs are not coordinated with those of the conventional voltage regulation devices, their interference is of a great concern [1]-[6]. Protective relay coordination is also of interest.

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In order to investigate the above mentioned problems, electromagnetic transient (EMT) simulations which give detailed three-phase waveforms of voltages and currents are required. To this end, EMT simulation models of distribution substations and SVRs have been developed. Interference between conventional voltage regulation devices and a large-scale PV power generation system is reproduced by an EMT simulation using the developed models.

II. Developed models

A. Distribution Substation Model

The distribution substation steps down the voltage received from a transmission line into the distribution voltage which is 6.6 kV, 22 kV or 33 kV in the case of Japan. In most cases, 6.6 kV is used. The voltage conversion is performed by main transformers in the distribution substation, and each of them called a “bank” supplies power to four to eight distribution lines (feeders). Each main transformer is equipped with an LRT, an on-load tap changer, and the sending-out voltage of distribution lines connected to a common main transformer are regulated by its LRT. Thus, the sending-out voltage regulation of distribution lines is performed bank by bank, and the voltage of each distribution line cannot be regulated independently. The LRT automatically changes its tap position in order to heighten the voltage when the bank load is heavy and to lower the voltage when the bank load is light so that the voltages along the distribution lines fall into an appropriate range. [7]

For the LRT control, the two major methods, the program-control method and the line-drop compensator (LDC) method,

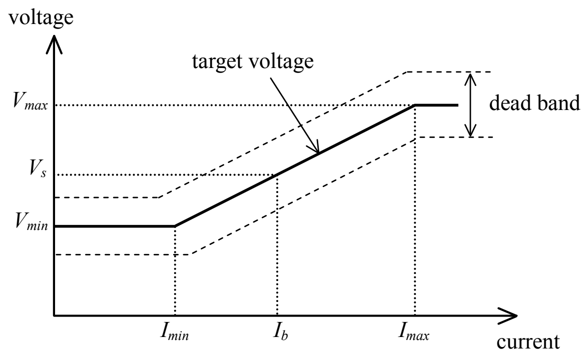

Fig. 1. Voltage-current relationship illustrating the operating principle of the LDC method.

are well-known. The program-control method changes the tap position of the LRT according to a pre-determined time schedule, while the LDC method changes the tap position depending on the measured current value. The developed distribution substation model supports both methods. Since the implementation of the program-control method is trivial, the LDC method is described below.

The LDC method first calculates the target value of the sending-out voltage from the measured current value, and the subsequent automatic voltage regulating relay then compares the measured voltage value with the target value obtained so as to find which direction to change the tap position.

Fig. 1 shows the voltage-current relationship that illustrates the operating principle of the LDC method. As parameters to set, $V_{\min}$ and $I_{\min}$, the sending-out voltage and current when the load is the lightest and $V_{\max}$ and $I_{\max}$, the sending-out voltage and current when the load is the heaviest are given. Using the straight line connecting the points ($I_{\min}$, $V_{\min}$) and ($I_{\max}$, $V_{\max}$), the target value V_s of the sending-out voltage is found based on a measured current value I_b, and the upper limit $V_{\max}$ and the lower limit V_{min} are applied so as to obtain the final value of V_s. The procedure mentioned here can be expressed by the following equations:

(a) when $I_{\mathrm{b}} < I_{\min}$

$$V_s = V_{min} \tag{1}$$

(b) when $I_{\min} \le I_{\mathrm{b}} \le I_{\max}$

$$V_s = Z \cdot \left(I_b - I_{\min} \right) + V_{\min} \tag{2}$$

(c) when $I_{\max} < I_{\mathrm{b}}$

$$V_s = V_{\max} \tag{3}$$

where the slope of the straight line, that is, the impedance characteristic Z of the bank is given by

$$Z = \frac{V_{\max} - V_{\min}}{\mathrm{I}_{\max} - I_{\min}} \tag{4}$$

An automatic voltage regulating relay, referred to as 90R hereafter, is used for issuing a tap-change command based on the target value V_s sent from the LDC component. The 90R compares the measured voltage value V with the target value V_s. If $V < V_s$, a command to raise the tap position by one step is issued. If $V > V_s$, a command to lower the tap position by one step is issued. To avoid unnecessary operations due to temporary voltage variations, a dead band is set with respect to the target-voltage line as shown in Fig. 4. When the measured voltage V is out of this band for a certain period of time, a command to raise or lower the tap position is issued.

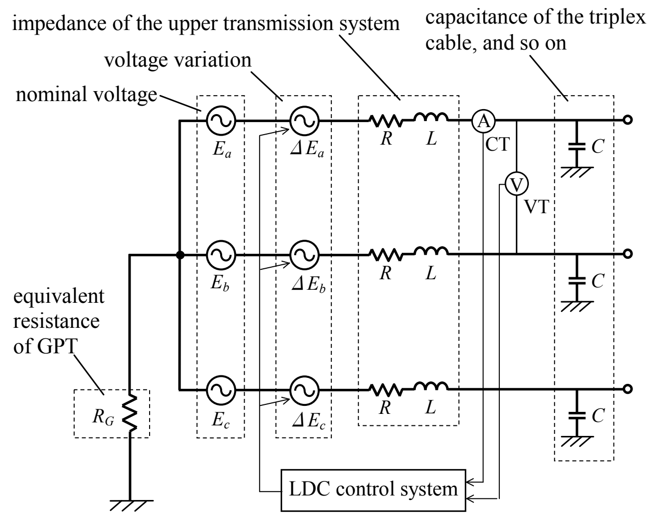

Fig. 2. Distribution substation model.

To model the distribution substation, it should be noted that we are interested in voltages along a distribution line which is connected to the distribution substation, and we are not interested in voltages in the distribution substation itself. Therefore, the model should represent the following two points: (i) power supply to supply power to the distribution line and (ii) impedance seen from the distribution line. The former can be represented by a three-phase voltage source, but its amplitude should be controllable so as to reproduce tap changes of the LRT. The latter can be represented by a series *R*-*L* branch for each phase. Its impedance takes into account the impedance of the main transformer and the short-circuit impedance of the upper transmission system seen from the distribution substation.

Fig. 2 shows the distribution substation model developed considering the points discussed above. The model consists of the two parts: the electrical-circuit part and the control-system part.

The main components of the electrical-circuit part are two sets of a three-phase voltage source and series *R*-*L* branches for the three phases. The three-phase voltage source designated by E_a, E_b and E_c represents the nominal voltage, 6.6 kV, 22 kV or 33 kV in this case. The other three-phase voltage source designated by ΔE_a, ΔE_b and ΔE_c represents voltage variations due to tap changes of the LRT. The impedance of the series *R*-*L* branches designated by R and L is calculated as the sum of the impedance of the main transformer and the short-circuit impedance of the upper transmission system. Those values should be appropriately converted to values seen from the distribution line considering the turn ratio of the main transformer.

It is common in Japan to use a triplex cable buried underground for sending out a distribution line. The capacitances labeled by C represent the capacitances of the triplex cable and the stray capacitances of the main transformer and other substation equipment. Normally, each bank is equipped with a grounded potential transformer (GPT) to detect distribution-line faults to the ground. The resistance R_G which is connected to the neutral point of the Y-connected three phase voltage source equivalently represents the tertiary terminating resistance of the GPT. As shown in Fig. 3, the GPT has a Y-connected primary, a Y-connected secondary, and an open-delta tertiary winding, and the tertiary winding is terminated by the resistor R_D. The neutral points of the primary and the secondary winding are directly grounded. Considering this winding connection, the effect of R_D can be converted to the resistance R_G that is inserted between the neutral point of the Y-connected three phase voltage source and the ground using the following equation:

$$R_G = \frac{1}{9}\left(\frac{n_1}{n_3}\right)^2 R_D \tag{5}$$

where n_1 is the number of turns of the primary winding and n_3 is that of the tertiary winding both of the GPT. Normally, the

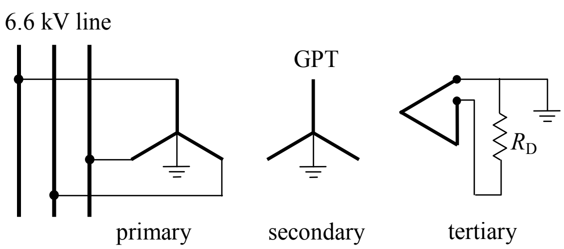

Fig. 3. Grounded potential transformer (GPT).

value of R_D is 25 Ω or 50Ω, and n_1 and n_3 are calculated from their nominal voltages in the following way: $n_1 = 6600/\sqrt{3}$ and $n_3 = 110/3$. Therefore, the value of R_G is calculated to be several ten kΩ. Although the 6.6-kV distribution systems in Japan are called ungrounded systems, they are actually grounded through a several ten kΩ resistance.

Fig. 4 shows the control-system part of the distribution substation model. As shown in Fig. 2, the sending-out voltage and current of the main transformer are measured respectively by the voltage transformer (VT) and the current transformer (CT). The measured voltage and current values are then sent to the control-system part that controls the tap position of the LRT. In this part, the above mentioned algorithms of the LDC and the 90R are implemented in the form of control blocks.

In the LDC part, the measured voltage value obtained by the VT is converted to the target voltage value using (1)-(3). In the 90R part, the measured current value obtained by the CT is compared with the target voltage value calculated by the LDC part taking the dead band into account, and a signal to indicate which direction to change the tap position is generated. The duration of this signal is measured using a counter block. If the duration exceeds a predetermined value given as a model parameter, then a command to raise or lower the tap position of the LRT is issued. Since the electric-circuit part of the developed model represents the tap-position change by the three-phase voltage source designated by ΔE_a, ΔE_b and ΔE_c, the command is converted to the corresponding values of ΔE_a, ΔE_b and ΔE_c and sent to those voltage source components.

The distribution substation is generally equipped with various protective relays. When studies involving faults are of interest, those protective relays should be represented in the model. At this writing, those protective relays are not implemented in the developed model, but the authors plan to

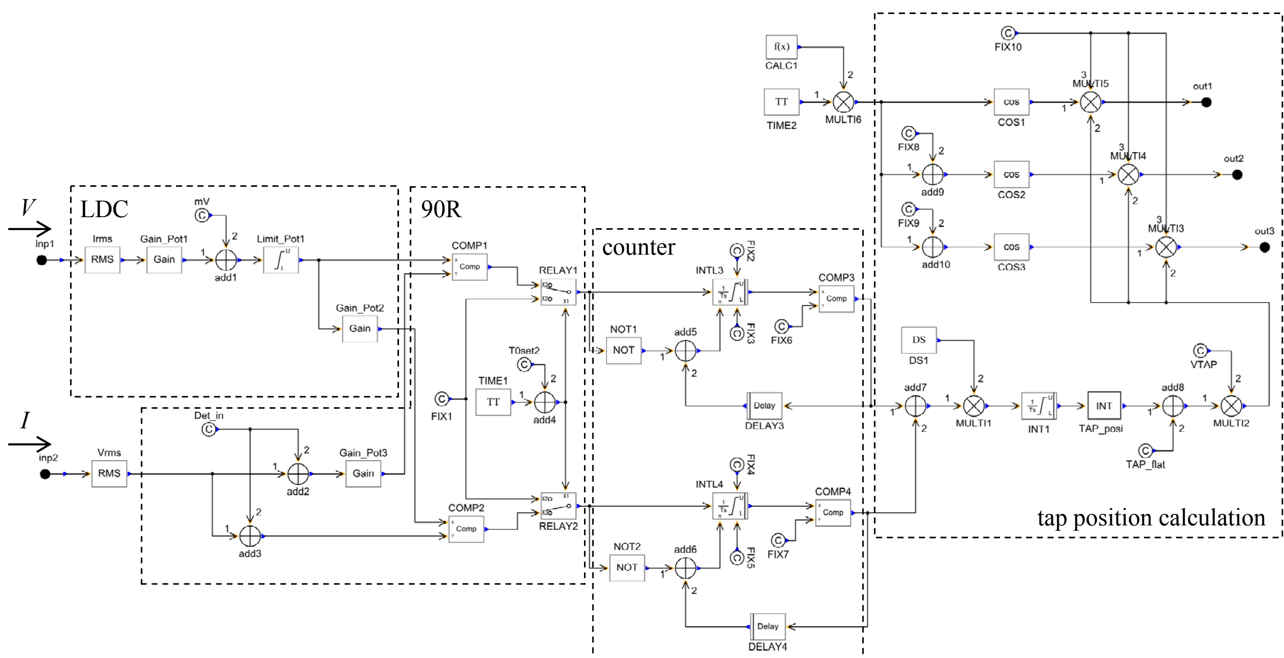

Fig. 4. Control-system part of the distribution substation model.

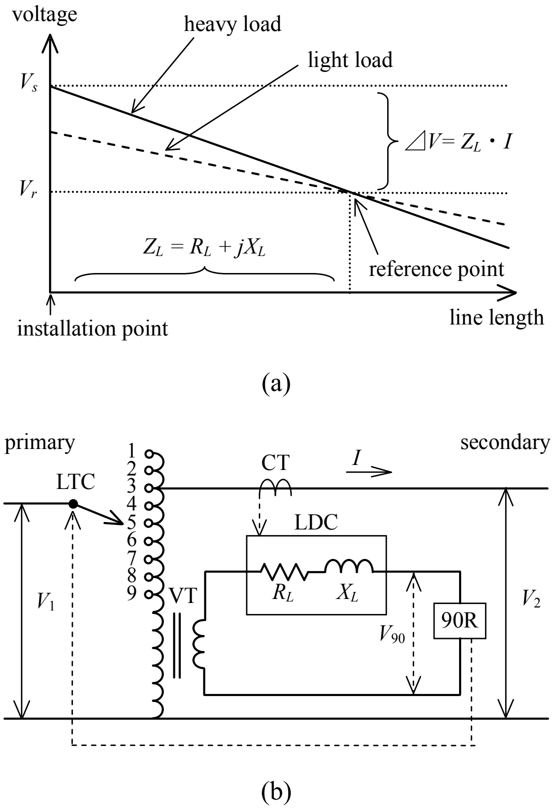

Fig. 5. Voltage regulation by an SVR. (a) shows the control algorithm of voltage regulation by an LDC method, and (b) shows the LTC and the low-voltage electrical circuit.

implement them in the future.

B. SVR model

The SVR is a Y-connected three-phase autotransformer with an on-load tap changer called an LTC. To regulate the voltages along a distribution line, it is inserted in series with and on the way of the line. The SVR changes the tap position of the LTC depending on the voltage and current at its installation point. The tap-position control is performed by an LDC method with a subsequent 90R in the same way as the tap-position control of the LRT in the distribution substation [8], [9].

As illustrated in Fig. 5 (a), the SVR generally uses the control algorithm that regulates the voltage at the center of the loads connected on the load side of the distribution line. The load-center voltage V_r is estimated by

$$V_r = V_s - Z_L \cdot I \tag{6}$$

where $Z_L = R_L + jX_L$ is the impedance of the distribution line between the installation point of the SVR and the load center, V_s is the voltage measured by the VT at the secondary side (= V_2), and I is the current measured by the CT. This calculation is usually performed by an actual low-voltage electrical circuit as shown in Fig. 5 (b). A small voltage which is in proportion to V_2 is generated by the secondary-side VT, and the impedance of the 90R is set to the value which corresponds to the load impedance. And an actual *RL* branch is inserted between them to simulate the voltage drop of the distribution

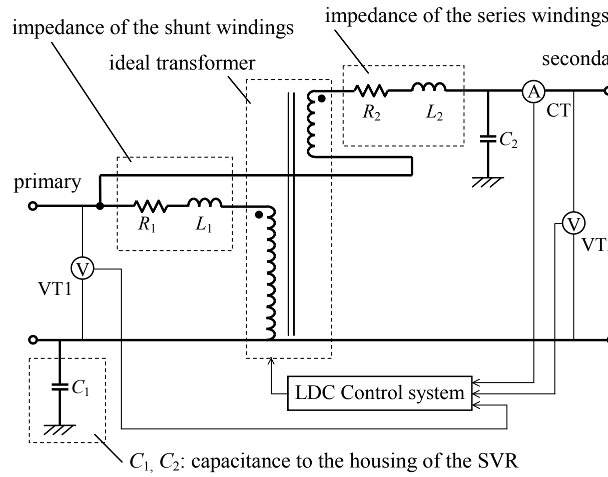

Fig. 6. One phase of the SVR model.

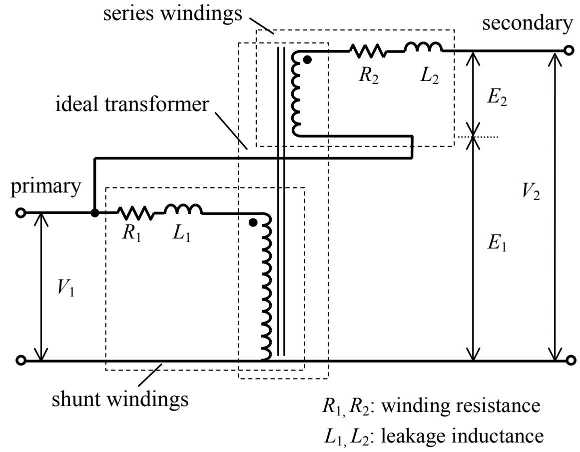

Fig. 7. Equivalent circuit of the autotransformer windings.

line. In this way, V_{90} which corresponds to the load-center voltage (V_r) is obtained as the voltage across the 90R.

In the 90R, V_{90} is compared with the target value V_{ref}. If $V_{90} < V_{ref}$, a command to raise the tap position by one step is issued. If $V_{90} > V_{ref}$, a command to lower the tap position by one step is issued. To avoid unnecessary operations due to temporary voltage variations, a dead band is set about V_{ref}. When two or more SVRs are inserted at different points of a distribution line, hunting of those SVRs are of concern. Thus, the dead band is usually set to a value greater than 1 %, and different time limits are set for different SVRs. The time limits are usually set to values longer than 45 seconds.

Fig. 6 shows the developed SVR model. This model also consists of an electrical-circuit part and a control-system part.

The electrical-circuit part basically represents the Y-connected three-phase autotransformer of the SVR. One phase of the autotransformer, consisting of a series winding and a shunt winding, is represented by the equivalent circuit shown in Fig. 7. This equivalent circuit of the windings consists of an ideal transformer, the winding resistance and leakage inductance of the series winding, and those of the shunt winding. If the series and shunt windings are viewed as one single winding, that winding has capacitance to the housing of

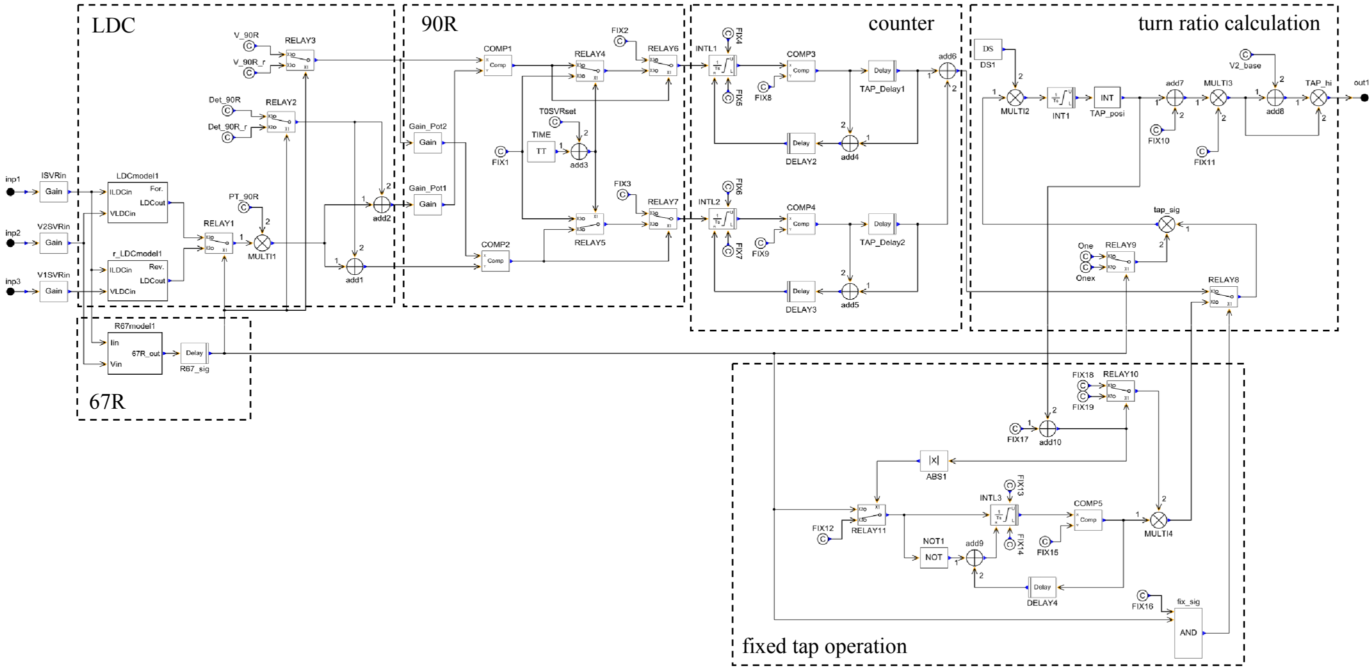

Fig. 8. Control-system part of the SVR model.

the SVR. The capacitance is lumped into two capacitances and added to both sides in the model. The tap-position change of the LTC is equivalently represented by changing the turn ratio of the ideal transformer.

The turn ratio n can be expressed by the following equation using the primary voltage V_1, the secondary voltage V_2, the shunt-winding voltage E_1, and the series-winding voltage E_2 (see Fig. 7 for these symbols):

$$n = \frac{E_2}{E_1} = \frac{V_2 - V_1}{V_1} \tag{7}$$

The value of V_1 is obtained by the voltage of the tap position, and that of V_2 by the nominal voltage of the secondary side of the SVR. Therefore, the turn ratio n can be calculated by a tap position determined by the control-system part using (7), and the turn ratio calculated is then used by the ideal transformer of the model. Precisely speaking, the winding resistance and the leakage inductance of the series winding and those of the shunt winding vary with respect to n. However, these variations are ignored in the model, since they are fairly small.

Fig. 8 shows the control-system part. The voltages at the primary and the secondary side are measured by the VTs, and the current at the secondary side is measured by the CT. These measured values are then sent to the control-system part. As shown in Fig. 8, the control blocks of the LDC and the 90R are implemented. Since the algorithm of these control blocks are almost the same as those of the control-system part of the distribution substation models, the specific features of the SVR and its implementation are described in the following.

A distribution network is often reconfigured by switchgears, and the power flow direction can thus be reversed at the point of an SVR. Most SVRs are able to cope with this by detecting the power flow direction. There are two major methods to cope with this reversed power flow. One is called the fixed-tap

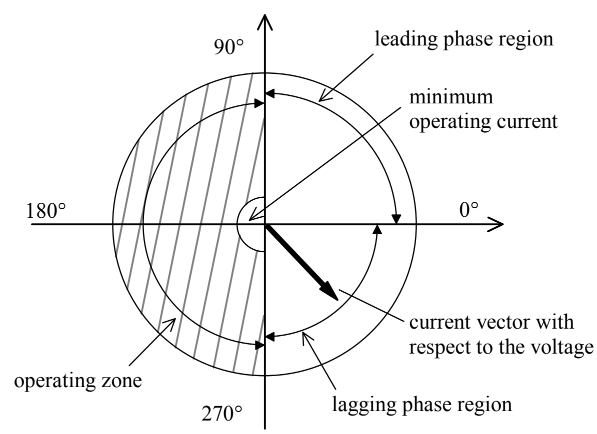

Fig. 9. Detection algorithm of the reverse power flow by the 67R.

method and the other is called the bi-directional voltage regulation method. When the power flow is reversed, the former method fixes the tap of the LTC at a predetermined position. The latter changes the control target from the secondary side of the SVR to its primary side.

The voltage and current measured at the secondary side of the SVR are sent also to a reverse current relay, referred to as 67R hereafter. Using the voltage and current, the 67R determines the direction of the power flow through the SVR based on the diagram shown in Fig. 9. To avoid unnecessary operations, a minimum current value and a time limit are taken into account in the detection. When a reverse power flow is detected, this signal is sent to the LDC unit. Upon reception of the reverse power-flow signal, the LDC unit changes its behavior depending on the operating mode specified. The developed SVR model supports both of the fixed-tap method and the bi-directional voltage regulation method mentioned above, and one of the methods can be specified as its

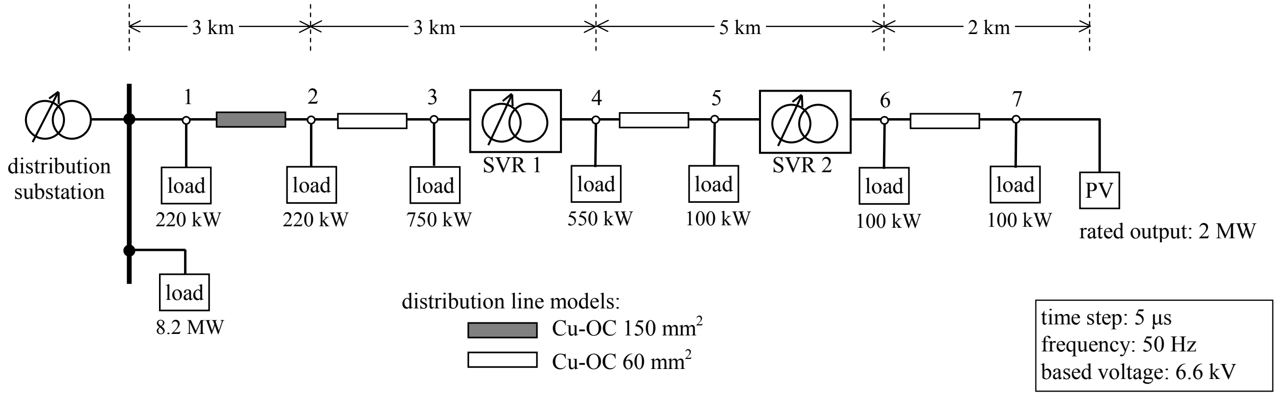

Fig.10. Single-line diagram of a simple 6.6-kV distribution line.

operating mode. If the fixed-tap mode is chosen, upon reception of the reverse power-flow signal, the tap is fixed to a predetermined position, that is, the turn ratio of the ideal transformer is fixed to a predetermined value. If the bi-directional voltage regulation mode is chosen, upon reception of the reverse power-flow signal, the target of the voltage regulation is changed from the secondary side of the SVR to the primary side. When the primary-side voltage is regulated, raising the tap position corresponds to lowering the primary-side voltage. This is opposite from the case where the secondary-side voltage is regulated. Thus, this opposite operation is considered when the equivalent turn ratio is calculated in the model. In an actual SVR, changing the tap position is a mechanical process and thus takes a certain period of time. The delay due to this mechanical process is represented by a simple time-delay block whose delay time is specified by the user in the developed model.

III. Simulation

In Japan, interference between conventional voltage regulation devices and a large-scale PV power generation system was reported by a distribution operator, and it is estimated that this kind of problem will increase in the near future. In this section, this interference is reproduced by an EMT simulation using the developed models. The simulation is carried out by the EMT analysis program XTAP (eXpandable Transient Analysis Program) [10].

A. Simulation Conditions

Fig. 10 shows the single-line diagram of the simulation case. This is a simple 6.6-kV distribution line with no branches. The length is 13 km, and two SVRs are inserted to compensate the voltage drop due to the long length. In the simulation, the distribution line is divided into four sections, and each of them is represented by a π-equivalent circuit. The line-constants of the distribution line was calculated by a line-constants calculation program assuming the wire arrangement shown in Fig. 11. The distribution substation that sends out this distribution line is represented by the developed model described in Section II.A, and its model parameters are set as shown in Table I. The SVRs are represented by the developed model described in Section II.B, and the model parameters

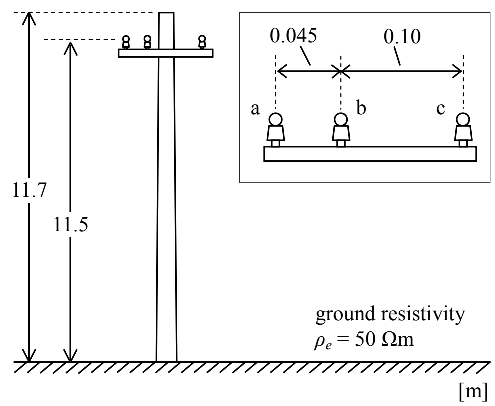

Fig. 11. Wire arrangement used for the line-constants calculation.

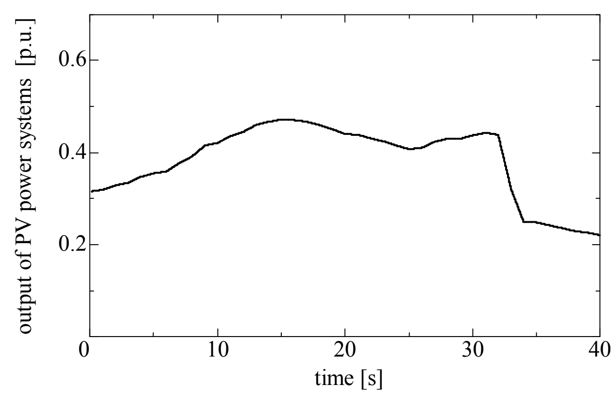

Fig. 12. Assumed time variations of the PV output.

used are shown in Table II. A large-scale PV generation system is connected at the remote end. Its rated output is 2 MW which belongs to the largest class for the 6.6-kV distribution line. It is assumed that the output of the PV generation system varies with respect time as shown in Fig. 12, where the output initially increases slowly and then drops rapidly at around t = 33 seconds. The PV generation system is represented by the model proposed in [11]-[14]. The loads are represented by three-phase resistances.

B. Simulation Results

Under the conditions mentioned above, an EMT simulation

TABLE I
PARAMETERS OF THE DISTRIBUTION SUBSTATION MODEL

Nominal voltage [V]		6600
Capacity of the main transformer [MVA]		15
Impedance characteristic Z	Max voltage [V]	6900
	Minimum voltage [V]	6400
	Max current [A]	1000
	Minimum current [A]	200
Dead band [%]		1.1
Time limits [s]		20

TABLE II
PARAMETERS OF THE SVR MODEL

	SVR 1	SVR 2
Rated capacity [kVA]	3000	3000
Rate primary voltage [V]	6600	6600
Voltage between taps [V]	100	100
Reference voltage [V]	6780	6720
Initial tap position	5	4
Time limits [s]	45	60
Dead band [%]	1.5	1.5
Operating mode for a reverse power flow	Fixed-tap mode	
Fixed-tap position	3	4
Time delay for the tap changing [s]	4.0	4.0

has been carried out to obtain the voltages and currents at the nodes numbered as shown in Fig. 10. The calculated time variations of these voltages in r.m.s. are shown in 13, and those of the currents are shown in Fig 14. As the output from the PV generation system increases around t = 0-15 seconds, the voltages at points close the PV end increase. The nodes closer to the PV end shows larger increase. In order to regulate the voltages within a designated range, the LRT of the distribution substation and the SVRs operate to lower the voltages. The voltage drops marked by A in Fig. 13 are due to the fact that SVR 1 changes its operating mode to the fixed-tap mode, since it detects a reverse power flow. In this particular case, SVR 1 changes the tap position of its LTC from 5 to 3, and this lowers the voltage by about 200 V. On the other hand, the voltage drops marked by B in Fig. 13 are caused by an operation of the LRT in the distribution substation.

Fig. 15 shows the three-phase wave forms of the voltages which measured at the output end of the PV generation system when the latter voltage drops are caused. In this case, it can be seen that the voltage variations according to the tap change of the LRT in the distribution substation do not give a little influence on these waveforms. Since the control and protection systems of PCSs are performed at a high speed based on the three-phase waveforms, these EMT simulation models are required for simulations such as this.

Due to the increase of the output from the PV generation system, the bank current decreases, and the target voltage of

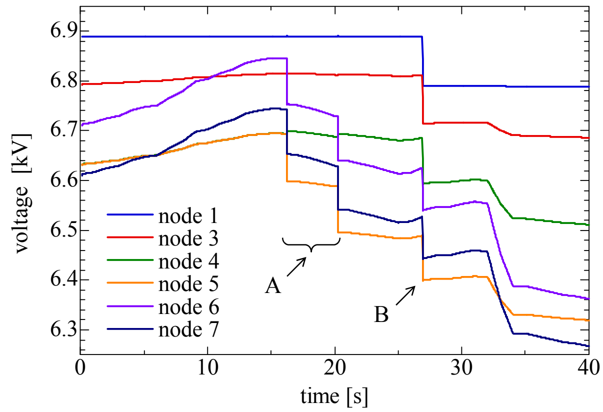

Fig. 13. Calculated time variations of the node voltages.

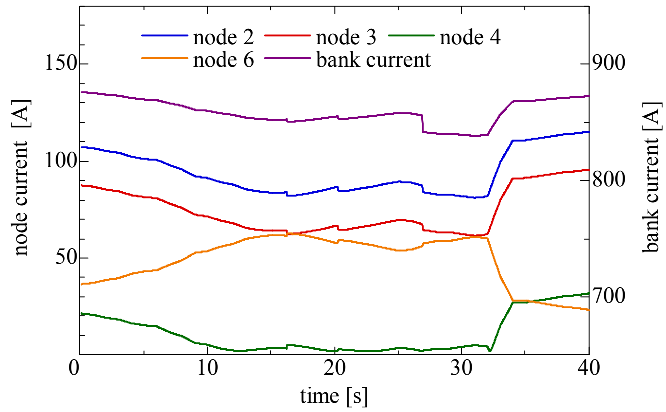

Fig. 14. Calculated time variations of the node currents.

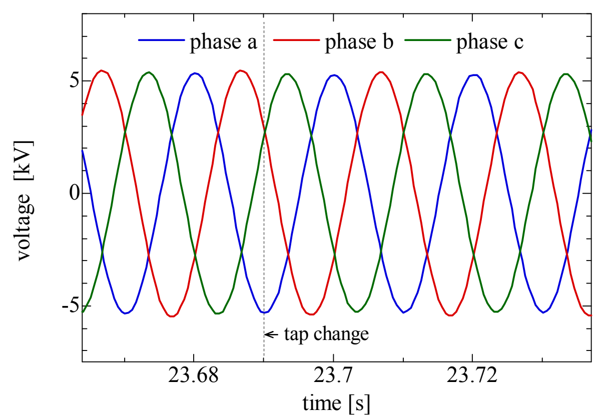

Fig. 15. Three-phase waveforms of the voltages measured at the output end of the PCS.

the LRT becomes smaller by this decreased current. In this way, these conventional voltage regulation devices operate in response to the slow voltage rise due to the reverse power flow from the PV generation system. However, a large voltage drop is observed at points close to the PV end, when the output from the PV generation system rapidly decreases at around t = 33 seconds due to the PV output scenario shown in Fig. 12. The voltage at Node 7 especially drops compared with its initial value. This is because the conventional voltage regulation devices, the LRT in the distribution substation and the SVRs, cannot respond to this kind of rapid voltage variation. In such an event, the consumer-end (outlet) voltage may deviate from the designated voltage range defined by law. The simulation result shown above closely reproduces an interference problem reported by a distribution operator in Japan, although its detailed data cannot be disclosed due to security reasons.

IV. CONCLUSIONS

This paper has presented electromagnetic transient (EMT) simulation models of distribution substations and Step Voltage Regulators (SVRs) for simulation studies of interference with photovoltaic (PV) power generation systems and so on. Using the developed models, the result of an EMT simulation successfully reproduces an actual interference problem reported by a distribution operator in Japan. Since the distribution substation and the SVR are essential elements to constitute distribution systems, these developed models are useful to construct the foundation of the EMT simulations for distribution systems.

V. FUTURE WORK

The authors have been developing other EMT simulation models for distribution systems such as static synchronous compensators (STATCOMs) or wind power generators. In the future, more complex simulations using these developed models would become possible.

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