분산형전원이 도입된 배전계통의 리얼타임 최적전압조정을 위한 부하구간 모델링방법

論 文
48A - 6 - 6

A Modeling Method of Load Section on High Voltage Distribution Line Integrated with Dispersed Generation System for Real-Time Optimal Voltage Regulation

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Abstract - It is known[3] that the LDC(Line-Drop Compensator) becomes to lose the function of proper voltage regulation for its load currents due to the real and reactive power generated by DGS(Dispersed Generation System), when DGS is introduced into the power distribution system of which the voltage is controlled by LDC. Therefore, in that case, it is very difficult to regulate the distribution line voltage properly by using LDC. One possible solution for this problem is the real-time voltage regulation method which is to optimally regulate the sending-end voltage in real-time by collecting the real-time load data of each load section between measuring points and by calculating the optimal sending-end voltage value from them. For this, we must know the real-time load data of each load section. In this paper, a modeling method of representing a load section on high voltage line with DGSs as an equivalent lumped load is proposed for gaining the real-time load data. In addition a method of locating the measuring points is proposed. Then, these proposed methods are evaluated through computer simulations.

Key Words : Power Distribution System, Dispersed Generation System, Load Section Modeling, Voltage Regulation

1. Introduction

Employing DGS (Dispersed Generation System) in electric power distribution system has drawn intensive attention since it can be incorporated with various power resources. When DGSs are introduced into a traditional distribution system, their impacts on its voltage regulation must be considered carefully, because the real and reactive powers generated by them flow into the distribution system. DGS means any source of electrical energy connected directly to a utility distribution system, such as co-generation system, fuel cell generation system, and so on.

Nowadays, most distribution substations are equipped with LRT(Load-Ratio control Transformer) and LDC(Line-Drop Compensator). Sending-end voltage at substation is regulated automatically by them to maintain a proper voltage level which is predetermined for a varying load current at the secondary side of LRT by internal setting coefficients of LDC. That is, when the load current increases, they boost the sending-end voltage to compensate the voltage drop on the distribution line, and vice versa. This voltage regulation method is called the LDC method[1][2]. If DGSs are introduced into the distribution system of which the line voltage is controlled by this method, the LDC becomes to lose the function of proper voltage regulation and the voltage on the distribution circuit may violate the permissible limit which the terminal voltage of low voltage customers must be maintained[3]. Because the LDC operates for the load current of the power distribution circuit with DGSs, of which internal coefficients are set to produce a proper sending-end voltage for the varying load current of the power distribution circuit without DGSs.

As one possible method for solving this problem, a real-time optimal voltage regulation method can be considered like Fig. 1. That method is to optimally regulate the sending-end voltage in real-time by collecting the real-time load data of each load section between measuring points and by calculating the optimal sending-end voltage value from them. For this, we must know the real-time load data of each load section to calculate the optimal sending-end voltage. In this paper, a modeling method of representing a load section on high voltage line with DGSs as an equivalent lumped load is proposed for gaining the real-time load data. Also, a method of locating the measuring points is proposed. Then,

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接受日字 : 1998年 12月 3日
最終完了 : 1999年 5月 13日

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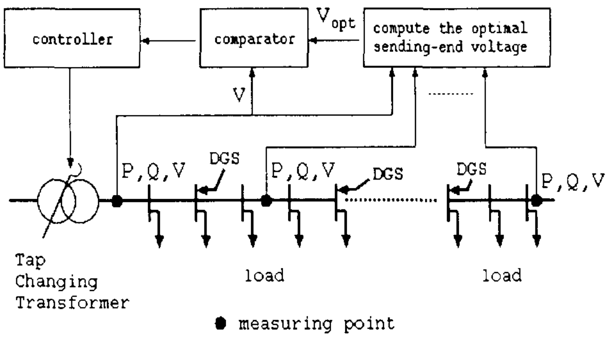

Fig. 1 Concept of real-time optimal voltage regulation for sending-end voltage of high voltage line with DGSs

2. Modeling of Load Section on High Voltage Line with DGSs

A traditional method for modeling of load section on high voltage distribution line is that the line is divided into some load sections by measuring equipments and each load section is modeled as the difference of magnitude of currents flowing on both measuring points under the condition that the power flow on that line is uni-diretional and the phase angle of any line current on that line is always identical[4][5]. But, this method can not be applied to high voltage distribution line with DGSs, because the power flow of that line with DGSs which are arbitrary operating power factors becomes bidirectional and the phase angle of any line current on that line is always not identical. Therefore, in this section we propose a modeling method for representing a load section on high voltage distribution line with DGSs as an equivalent lumped load.

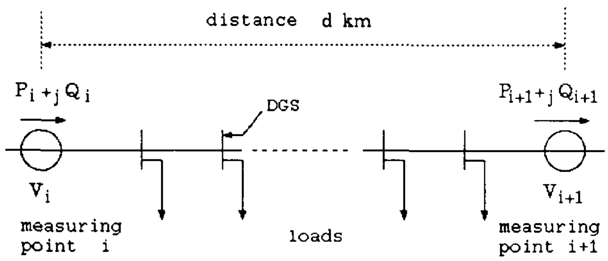

Fig. 2 A load section of high voltage distribution line with DGSs

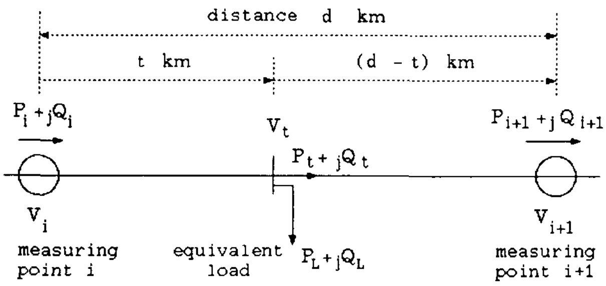

Fig. 3 A model of the load section in Fig.2 represented as an equivalent lumped load and its equivalent distance

First, let's consider a load section as shown in Fig. 2. In Fig. 2, the voltage magnitudes and the real & reactive powers at measuring points i and i+1 are expressed as V_i, V_{i+1}, P_i, P_{i+1}, Q_i, Q_{i+1}, respectively. The line impedance per km is r+jx. We assume that they are known through measuring equipments. Then, the load section with distributed loads in Fig. 2 is represented as an equivalent lumped load and its equivalent distance as in Fig. 3. That is, Fig. 2 can be modeled as Fig. 3 by obtaining the equivalent lumped load P_L+jQ_L, the equivalent distance t and the voltage V_t of equivalent load point.

Power flow equations called as DistFlow equation[6] for solving these are as follows:

$$P_t = P_i - \frac{tr(P_i^2+Q_i^2)}{V_i^2} - P_L \tag{1}$$

$$Q_t = Q_i - \frac{tx(P_i^2+Q_i^2)}{V_i^2} - Q_L \tag{2}$$

$$V_t^2 = V_i^2 - 2t(rP_i + xQ_i) + \frac{t^2(r^2+x^2)(P_i^2+Q_i^2)}{V_i^2} \tag{3}$$

$$P_{i+1} = P_t - \frac{r(d-t)(P_t^2+Q_t^2)}{V_t^2} \tag{4}$$

$$Q_{i+1} = Q_t - \frac{x(d-t)(P_t^2+Q_t^2)}{V_t^2} \tag{5}$$

$$V_{i+1}^2 = V_t^2 - 2(d-t)(rP_t + xQ_t) + \frac{(d-t)^2(r^2+x^2)(P_t^2+Q_t^2)}{V_t^2} \tag{6}$$

By using $\frac{{P_t}^2+{Q_t}^2}{{V_t}^2} = \frac{P_{i+1}^2+Q_{i+1}^2}{V_{i+1}^2}$ and eliminating P_t, Q_t, V_t, three equations for unknown parameter P_L, Q_L, t are obtained as follows :

$$P_L = P_i - P_{i+1} - r\left\{\frac{t(P_i^2+Q_i^2)}{V_i^2} + \frac{(d-t)(P_{i+1}^2+Q_{i+1}^2)}{V_{i+1}^2}\right\} \tag{7}$$

$$Q_L = Q_i - Q_{i+1} - x\left\{\frac{t(P_i^2+Q_i^2)}{V_i^2} + \frac{(d-t)(P_{i+1}^2+Q_{i+1}^2)}{V_{i+1}^2}\right\} \tag{8}$$

$$V_i^2 - 2t(rP_i + xQ_i) + \frac{t^2(r^2+x^2)(P_i^2+Q_i^2)}{V_i^2} = V_{i+1}^2 + 2(d-t)(rP_{i+1}+xQ_{i+1}) + \frac{(d-t)^2(r^2+x^2)(P_{i+1}^2+Q_{i+1}^2)}{V_{i+1}^2} \quad (9)$$

The parameter t satisfying the section condition $0 \le t \le d$ is calculated from Eq. (9). Then, the others are gained through Eqs. (7) and (8).

3. A Method of Locating the Measuring Points for Obtaining the t in $0 \le t \le d$

Here we consider the pattern that the equivalent load point t is solved in $0 \le t \le d$. The third terms in both sides of Eq. (9) are negligible. Because theses are much smaller than the first term and the second term in Eq. (9). Hence Eq. (9) can be written into Eq. (10).

$$V_i^2 - 2t(rP_i + xQ_i) = V_{i+1}^2 + 2(d-t)(rP_{i+1}+xQ_{i+1}) \quad (10)$$

Eq. (10) means that the t is determined at the intersection of two straight lines, $V^2=-2t(rP_i+xQ_i)+V_i^2$ and $V^2=-2t(rP_{i+1}+xQ_{i+1})+V_{i+1}^2+2d(rP_{i+1}+xQ_{i+1})$. From Eq. (10), the t is able to be obtained approximately like as Eq. (11).

$$t = \frac{V_i^2 - V_{i+1}^2 - 2d(rP_{i+1}+xQ_{i+1})}{2(rP_i+xQ_i) - 2(rP_{i+1}+xQ_{i+1})} \quad (11)$$

For obtaining the t of the condition $0 \le t \le d$, we know that either of the following inequalities must be satisfied.

$$-2(rP_i+xQ_i) < \frac{(V_{i+1}^2 - V_i^2)}{d} < -2(rP_{i+1}+xQ_{i+1}) \quad (12)$$

$$-2(rP_i+xQ_i) > \frac{(V_{i+1}^2 - V_i^2)}{d} > -2(rP_{i+1}+xQ_{i+1}) \quad (13)$$

The $-2(rP_i+xQ_i)$ of Eqs. (12) and (13) is the dV^2/dt at measuring point i on the t-V^2 curve of high voltage distribution line. The $-2(rP_{i+1}+xQ_{i+1})$ of Eqs. (12) and (13) is the dV^2/dt at measuring point i+1 on the t-V^2 curve of that line. The $(V_{i+2}^2-V_i^2)/d$ of Eqs. (12) and (13) is the slope of the straight line crossing measuring point i and measuring point i+1. Eqs. (12) and (13) mean that measuring points must be selected so that the slope of the straight line crossing measuring points is between the dV^2/dt at measuring point i and the dV^2/dt at measuring point i+1 on the t-V^2 curve of that line. This constraint always can be satisfied in the case of high voltage distribution line without DGSs like as Fig. 4. That is, the dV^2/dt on the t-V^2 curve of that line always satisfy Eq. (12) because $P_i \ge P_{i+1} \ge 0$ and $Q_i \ge Q_{i+1} \ge 0$ in that case. But, that cannot be satisfied in the case of high voltage distribution line with DGSs. Because inequalities $P_i \ge P_{i+1} \ge 0$ and $Q_i \ge Q_{i+1} \ge 0$ are not always satisfied owing to the output of DGSs flowing into

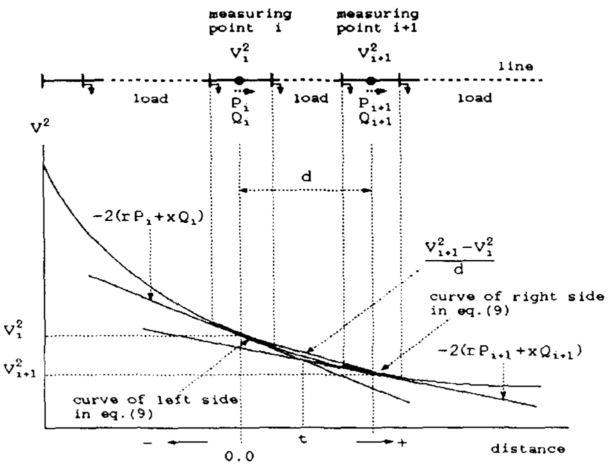

Fig. 4 Obtaining the t for a line without DGS

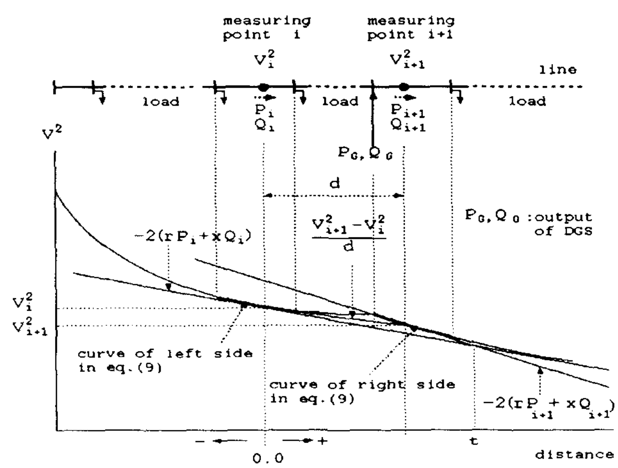

Fig. 5 Failing in obtaining the t for a line with DGS

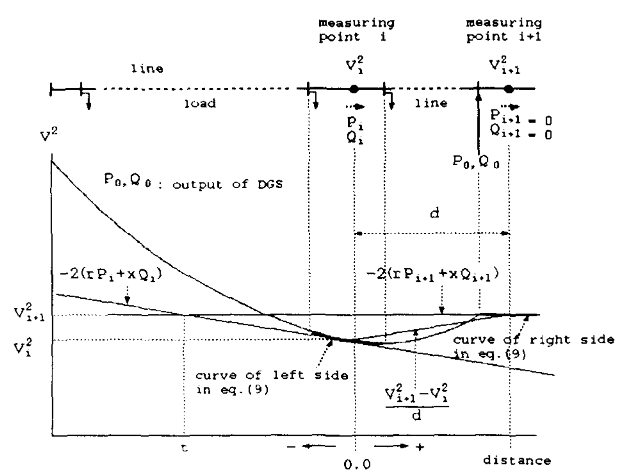

Fig. 6 Failing in obtaining the t for a line with DGS

that line and the dV^2/dt on the t-V^2 curve cannot satisfy Eq. (12) or Eq. (13) like as Fig. 5 and Fig. 6. For solving this problem we can see that two measuring points must be located just before and after the connection point of DGS. That is, if we know the real & reactive powers and voltage magnitude of those points, then, Eq. (12) or Eq. (13) for the left side and the right side of that point always can be satisfied.

4. Verification and Evaluation

For verification and evaluation of the proposed modeling method, we use a model such as high voltage distribution line shown in Fig. 7.

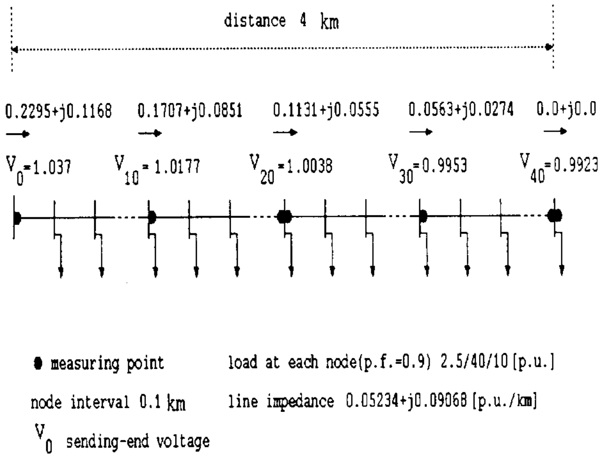

Fig. 7 A model of high voltage distribution line

In the above model, we consider that measuring points are seven including the sending-end point at substation and the line voltage is 6.6 kV and a constant power load of 2.5MVA×0.9(load power factor)÷40 MW is located at each node and forty loads of the same magnitude are uniformly distributed on the line with its distance interval 0.1 km and its power factor is lagging 0.9 and the line impedance is 0.05234+j0.09068 p.u./km. We use the p.u. Then, base MVA is 10 MVA and base voltage 6.6 kV. Simulation cases are as follows :

- case 1 : when DGS is not introduced.
- case 2 : when DGSs are connected into the node 20 and the node 40 with P_{G20} = 0.1 p.u. and P_{G40} = 0.1 p.u., respectively.
- case 3 : when DGS is connected into the node 40 with P_{G40} = 0.2 p.u.

The maximum introduction capacity of DGS unit is restricted to 0.2 p.u. considering the practical operating

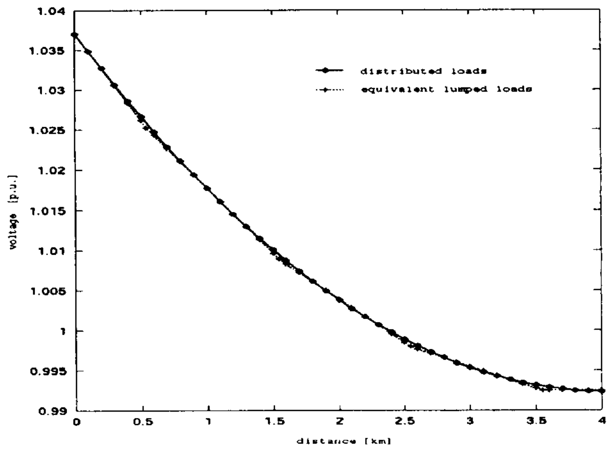

Fig. 8 Voltage profiles of the high voltage line in case 1

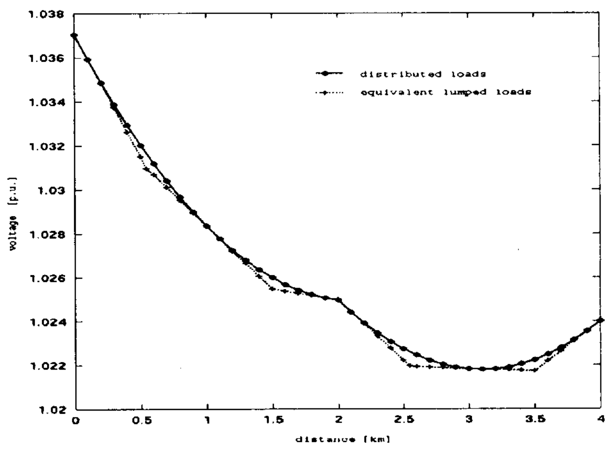

Fig. 9 Voltage profiles of the high voltage line in case 2

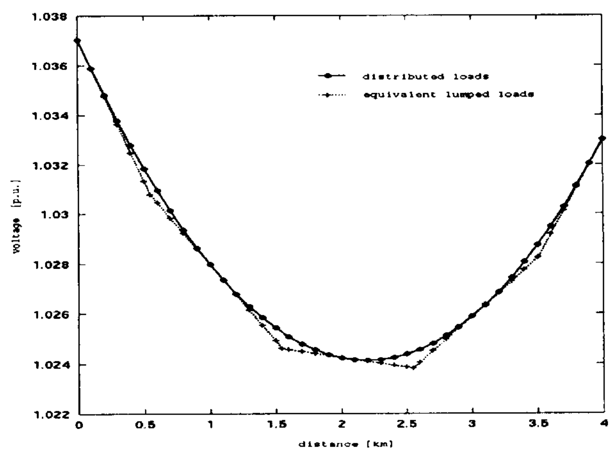

Fig. 10 Voltage profiles of the high voltage line in case 3

capacity of 6.6 kV high voltage line. Also, its operating power factor is considered as 0.9. Measuring points are just after sending-end point, node 10, node 30 and before/after node 20 and before node 40 from the results of the section 3. Simulation results for three cases are shown in Fig. 8, Fig. 9 and Fig. 10.

The sending-end voltage of the high voltage distribution line in Fig. 7 is considered as 1.037 p.u. In Fig. 8, Fig. 9 and Fig. 10, the dimension of the vertical axis is voltage magnitude(p.u.) and that of the horizontal axis is distance(km) of high voltage distribution line. The solid line is the voltage profile of the model in Fig. 7 with forty distributed loads. The dotted line is that of the model in Fig. 7 of which each load section is represented as an equivalent lumped load obtained by the proposed modeling method. The difference between two voltage profiles is about 0.0006 p.u. at most and this corresponds to 3.96 V at the level of 6.6 kV. This means that the proposed modeling method is very useful.

5. Conclusions

We have proposed a modeling method of representing a load section on high voltage distribution line with DGSs as an equivalent lumped load for gaining the real-time load data necessary to optimally regulate the sending-end voltage of that line with DGSs in real time. Also, a method of locating the measuring points was proposed.

Especially, it was verified through computer simulations that the proposed methods produced very small error enough to be negligible on the voltage profile and was very useful. In these simulations, we used seven measuring points. Of course, the error can be smaller if measuring points more than that are used. It is expected that this modeling method will be widely applied to not only the design and operation of the electrical power distribution system which many DGSs are introduced into but also feeder reconfiguration been doing frequently for loss minimization and etc.

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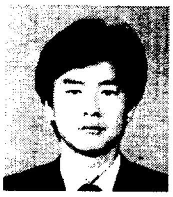

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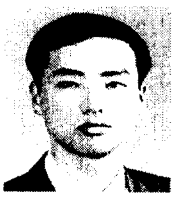

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