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The Identification of Transmission Line Overload and Fault Based on Ucosφ

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SUMMARY

Distance protection is a very important backup protection used in high-voltage power transmission line. Malfunctions of distance protection caused by overload during large-scale blackouts in the world expand the accident scope. For overload of transmission line, the load impedance decreases with the increasing of load and when it goes into action zone of distance protection, the distance protection will be mal-operated. Thus, it is important to identify line overload and fault to avoid mal-operation of distance protection.

Normally, load limit line is used to identify transmission line fault and normal overload in impedance plane. However, there are also some disadvantages. Firstly, the load limit line is difficult to avoid mal-operation of distance protection in overload condition. Secondly, it reduces the action zone of distance protection and weakens the distance protection performance of faults with high resistances.

Characteristics of transmission line overload and fault are analysed in voltage plane and criterion based on Ucosφ is proposed to identify overload and fault.

KEYWORDS

Distance protection, transmission line faults, overload, voltage plane, Ucosφ

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I. Introduction

Distance protection relay is an important backup protection and widely used on high voltage transmission lines. It identifies transmission line faults according to measurement impedance in R-X impedance plane. However, load encroachment may cause wrong tripping of transmission line distance protection relays, it can lead to cascades and expands power outage[1]-[3]. So it is important to identify overload and fault of transmission line to avoid wrong tripping of distance protection in overload condition. Normally, impedance blinder is used to avoid overload transmission line tripping, but it can't prevent cascading trip when overload caused by accident.

Some adaptive criterions in R-X impedance plane have been developed so far to adjust the boundary of distance relay in overload condition to avoid wrong tripping[4]-[10]. IEEE Power System Relaying Committee proposed several ways to set load blinding[4]. References [5] proposed advanced load blinding of distance relays based on physical grid limitation. Because impedance characteristics of fault and overload are similar in R-X impedance plane, load blinding reduces tripping zone of distance relays and drops fault identification sensitivity accordingly.

This paper proposes a new identification method of transmission line overload and faults based on Ucosφ in voltage plane. Firstly, transmission line overload and faults characteristics in voltage plane are analyzed. In transmission line overload condition, Ucosφ is directly proportional to power angle and it is bigger. For transmission lines faults, Ucosφ is directly proportional to fault resistance and it is smaller. Then the identification criterion is proposed and its performance is discussed. Finally, the protection criterion performance is tested extensively using RTDS-generated data, the simulation verified that the proposed criterion can identify transmission fault and overload accurately. The distance protection wrong tripping can be avoided in overload condition. The approach has been applied in protection devices which are used in 500kV transmission lines of china power grid.

II. The characteristic of transmission line load and faults in voltage plane

A. Impedance Characteristic of Transmission Line Load

For power system shown in Figure 1, the distance protection relay 1 is at M side of transmission line MN. $\dot{U}_{\mathrm{M}}$ and $\dot{I}_{\mathrm{M}}$ are voltage and current respectively of relay 1. $\dot{I}_{load}$ is load current. Z_{M} , Z_{N} , Z_{MN} are impedances of system M、N and line MN respectively. $\dot{E}_{\mathrm{M}}$ and $\dot{E}_{\mathrm{N}}$ are voltages of system M and N respectively.

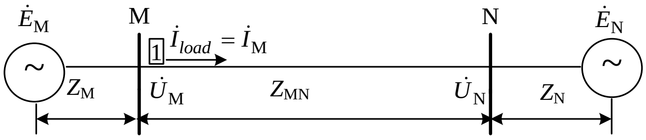

Figure 1. The sketch of normal system

The load impedance Z_{load} of distance relay 1 can be expressed as

$$Z_{load} = \frac{\dot{U}_{\mathrm{M}}}{\dot{I}_{\mathrm{M}}} \tag{1}$$

When $\arg Z_{\mathrm{M}} = \arg Z_{\mathrm{MN}} = \arg Z_{\mathrm{N}}$ .The trajectory of Z_{load} and operation zone of relay 1 are shown in Figure 2. When $\dot{I}_{\mathrm{M}}$ increases, Z_{load} decreases and moves along line OO' from O to O'. If Z_{load} encroach into tripping zone of distance protection relay, it trips the healthy line and may lead to cascades and blackout [11]. Normally, load blinder is used to identify transmission line faults and overload in impedance plane. On one hand, load blinder reduces the tripping zone of distance protection relay. On the other hand, it can't stop load encroachment caused by accident.

B.Voltage characteristic of transmission line load

For the system shown in Figure 1, load current $\dot{I}_{load}$ can be expressed as

$$\dot{I}_{load} = \frac{\dot{U}_{\mathrm{M}} - \dot{U}_{\mathrm{N}}}{Z_{\mathrm{MN}}} \tag{2}$$

When $\left|\dot{E}_{\mathrm{M}}\right| = \left|\dot{E}_{\mathrm{N}}\right|$ and $\arg Z_{\mathrm{M}} = \arg Z_{\mathrm{MN}} = \arg Z_{\mathrm{N}}$.

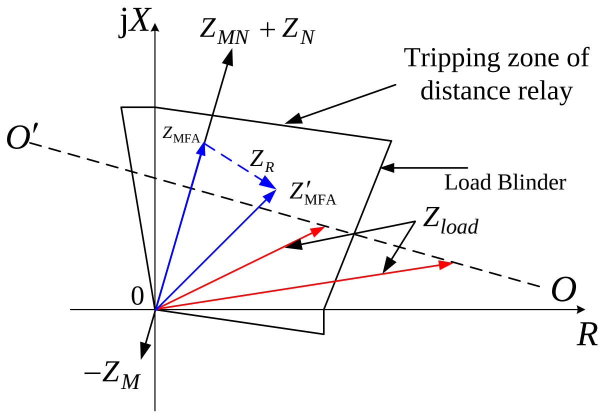

Figure 2. The trajectory of Z_{load} in R-X impedance plane

$$\dot{I}_{load}=\frac{\dot{E}_{M}-\dot{E}_{N}}{Z_{M}+Z_{MN}+Z_{N}}=\frac{\dot{E}_{M}-\dot{E}_{N}}{Z_{\Sigma}} \tag{3}$$

where $Z_{\Sigma}=Z_{M}+Z_{MN}+Z_{N}$

The relation between $\dot{E}_{M}$, $\dot{E}_{N}$, $\dot{I}_{load}$ and $\dot{U}_{M}$ is shown in Figure 3, it can be seen from it that $\left|\dot{E}_{M}-\dot{E}_{N}\right|=2E_{M}\sin\frac{\delta}{2}$ and δ is angle between $\dot{E}_{M}$ and $\dot{E}_{N}$. Formula (3) can be expressed as

$$\left|\dot{I}_{load}\right|=\frac{2E_{M}\sin\frac{\delta}{2}}{Z_{\Sigma}} \tag{4}$$

According to (4), $\dot{I}_{load}$ is proportional to $\sin\frac{\delta}{2}$. δ can be used to express the size of $\dot{I}_{load}$.

In Figure 3, the relation between $\dot{U}_{M}$ and $\dot{E}_{M}$ can be expressed as

$$E_{M}\sin\frac{\delta}{2}=U_{M}\cos\varphi \tag{5}$$

where $\varphi=\arg(\dot{U}_{M}/\dot{I}_{load})+(90^{\circ}-\varphi_{MN1})$, φ_{MN1} is positive sequence impedance angle of line MN.

Formula (4) can be expressed as

$$\left|\dot{I}_{load}\right|=\frac{2E_{M}\sqrt{1-(\frac{U_{M}\cos\varphi}{E_{M}})^{2}}}{Z_{\Sigma}}=\frac{2\sqrt{E_{M}^{2}-U_{M}^{2}\cos^{2}\varphi}}{Z_{\Sigma}} \tag{6}$$

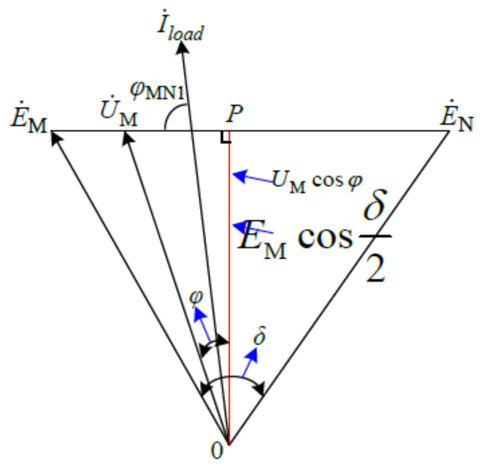

Figure 3. Voltage characteristic of load in voltage plane($ArgZ_{M}=ArgZ_{MN}=ArgZ_{N}$)

For no-load transmission line, $\dot{I}_{load}=0$ and $\delta=0^{\circ}$.

$$\frac{U_{\mathrm{M}}\cos\varphi}{E_{\mathrm{M}}}=\frac{U_{\mathrm{M}}\cos 0^{\circ}}{E_{\mathrm{M}}}=1 \tag{7}$$

When power system is near power angle stbility limit, $\delta=90^{\circ}$.

$$\frac{U_{\mathrm{M}}\cos\varphi}{E_{\mathrm{M}}}=\frac{U_{\mathrm{M}}\cos 90^{\circ}}{E_{\mathrm{M}}}=0.707 \tag{8}$$

Normally, $0^{\circ}\le\delta\le 90^{\circ}$,

$$0.707\le\frac{U_{\mathrm{M}}\cos\varphi}{E_{\mathrm{M}}}\le 1 \tag{9}$$

When $|\dot{E}_{\mathrm{M}}|=|\dot{E}_{\mathrm{N}}|$ and $\arg Z_{\mathrm{M}}\ne\arg Z_{\mathrm{MN}}\ne\arg Z_{\mathrm{N}}$, the relation between $\dot{E}_{\mathrm{M}}$, $\dot{E}_{\mathrm{N}}$, $\dot{I}_{load}$ and $\dot{U}_{\mathrm{M}}$ is shown in Figure 4.

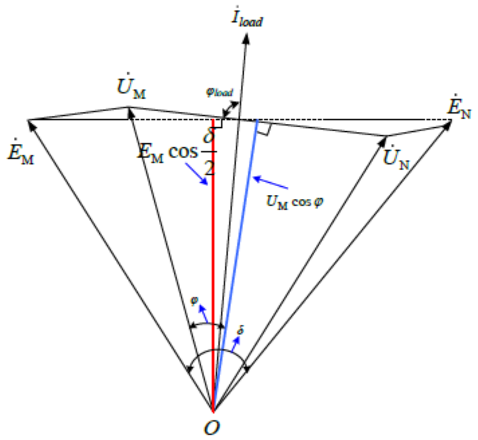

Figure 4. Voltage characteristic of load in voltage plane($ArgZ_{\mathrm{M}}\ne ArgZ_{\mathrm{MN}}\ne ArgZ_{\mathrm{N}}$)

When $|\dot{E}_{\mathrm{M}}|\ne|\dot{E}_{\mathrm{N}}|$ and $\arg Z_{\mathrm{M}}=\arg Z_{\mathrm{MN}}=\arg Z_{\mathrm{N}}$, the relation between $\dot{E}_{\mathrm{M}}$, $\dot{E}_{\mathrm{N}}$, $\dot{I}_{load}$ and $\dot{U}_{\mathrm{M}}$ is shown in Figure 5,

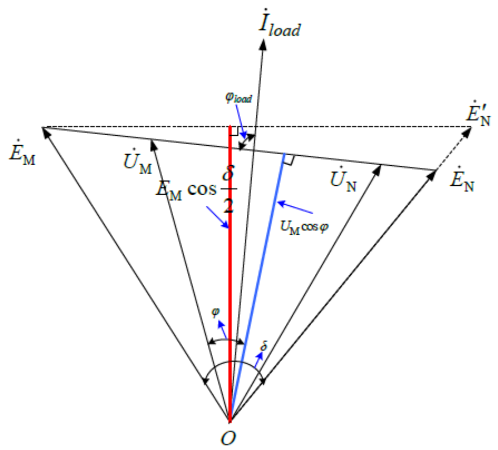

Figure 5. Voltage characteristic of load in voltage plane($|\dot{E}_{\mathrm{M}}|\ne|\dot{E}_{\mathrm{N}}|$)

According to Figure 3~5, for transmission line load, $E_{\mathrm{M}}\cos\frac{\delta}{2}$ is similar to $U_{\mathrm{M}}\cos\varphi$ and $\frac{U_{\mathrm{M}}\cos\varphi}{E_{\mathrm{M}}}$ is between 0.707 and 1.

C. Voltage Characteristic of Transmission Line Faults

For transmission line faults shown in Figure 6, R is fault resistance and F is fault point.

Take phase-A-to-ground fault as an example, the measurement impedance of distance relay 1 is

$$\dot{I}_{\mathrm{MA}}+3k\dot{I}_{\mathrm{M0}}=\frac{\dot{U}_{\mathrm{MA}}-\dot{U}_{\mathrm{FA}}}{Z_{\mathrm{MFA}}} \tag{10}$$

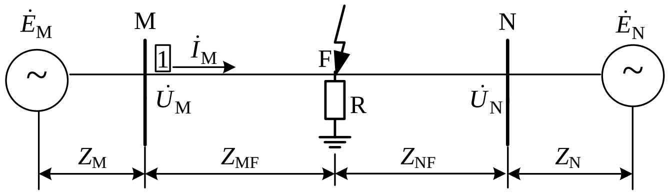

Figure 6. The sketch of power system with transmission line fault

where $k=\dfrac{z_0-z_1}{3z_1}$, z_1 and z_0 positive sequence impedance and zero sequence impedance of transmission line MN. $\dot{I}_{\mathrm{M0}}$ is zero sequence current and $3\dot{I}_{\mathrm{M0}}=\dot{I}_{\mathrm{MA}}+\dot{I}_{\mathrm{MB}}+\dot{I}_{\mathrm{MC}}$.

The relation between $\dot{I}_{\mathrm{MA}}$, $\dot{U}_{\mathrm{MA}}$, $\dot{U}_{\mathrm{FA}}$ is shown in Figure 7. In Figure 7, φ_{MA} can be expressed as

$$\varphi_{\mathrm{MA}}=\arg\left(\frac{\dot{U}_{\mathrm{MA}}}{\dot{I}_{\mathrm{MA}}+3k\dot{I}_{\mathrm{M0}}}\right)+(90^{\circ}-\varphi_{\mathrm{MFA}}) \tag{11}$$

It can be seen from Figure 7 that $U_{\mathrm{MA}}\cos\varphi_{\mathrm{MA}}$ is in direct proportion to $|\dot{U}_{\mathrm{FA}}|$ and fault resistance R.

When $R=0\Omega$, $\dfrac{U_{\mathrm{MA}}\varphi_{\mathrm{MA}}}{E_{\mathrm{MA}}}=0$. When $R=\infty$, $\dfrac{U_{\mathrm{MA}}\varphi_{\mathrm{MA}}}{E_{\mathrm{MA}}}=\cos\dfrac{\delta}{2}$.

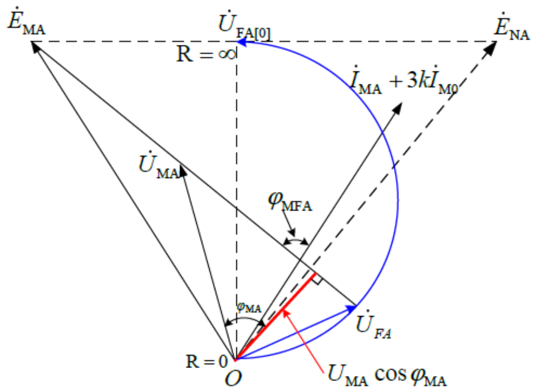

Figure 7. $U\cos\varphi$ of transmission line faults

For phase-to-phase short faults of transmission line (take AB short fault as an example), ther resistance between phases A and B is small and $|\dot{U}_{\mathrm{FAB}}|$ is small. $U_{\mathrm{MAB}}\cos\varphi_{\mathrm{MAB}}$ is also small, Normally, $\dfrac{U_{\mathrm{MAB}}\cos\varphi_{\mathrm{MAB}}}{E_{\mathrm{MAB}}}<0.05$.

III. The criterion of identifying transmission line overload and faults

According to analysis in section II, for different fault types of transmission line, voltage characteristics of Ucos is shown in Table 1.

It can be seen form Table I that Ucosφ can be used to identify transmission line faults and load. The identification criterion is

$$-0.2<\frac{U_{\mathrm{M}}\cos\varphi_{\mathrm{M}}}{E_{\mathrm{M}}}<0.5 \tag{12}$$

If the criterion is satisfied, it is a transmission line fault. For different transmission line faults, Ucosφ is different.

The transmission line load and single-phase-to-ground fault identification criterion I is

$$-0.2<\frac{U_{\mathrm{Mi}}\cos\varphi_{\mathrm{Mi}}}{E_{\mathrm{Mi}}}<0.5 \tag{13}$$

where i=A,B,C and $\varphi_{\mathrm{Mi}}=\arg\dfrac{\dot{U}_{\mathrm{Mi}}}{\dot{I}_{\mathrm{Mi}}+3k\dot{I}_0}+(90^{\circ}-\varphi_{L1})$.

TABLE I. Ucosφ OF DIFFERENT TRANSMISSION LINE FAULTS

Fault types	AG	BG	CG	AB ABG	BC BCG	CA CAG	ABC ABCG
$\frac{U_{\mathrm{MA}}\cos\varphi_{\mathrm{MA}}}{E_{\mathrm{MA}}}$	S	L	L	L	L	L	S
$\frac{U_{\mathrm{MB}}\cos\varphi_{\mathrm{MB}}}{E_{\mathrm{MB}}}$	L	S	L	L	L	L	S
$\frac{U_{\mathrm{MC}}\cos\varphi_{\mathrm{MC}}}{E_{\mathrm{MC}}}$	L	L	S	L	L	L	S
$\frac{U_{\mathrm{MAB}}\cos\varphi_{\mathrm{MAB}}}{E_{\mathrm{MAB}}}$	L	L	L	S	L	L	S
$\frac{U_{\mathrm{MBC}}\cos\varphi_{\mathrm{MBC}}}{E_{\mathrm{MBC}}}$	L	L	L	L	S	L	S
$\frac{U_{\mathrm{MCA}}\cos\varphi_{\mathrm{MCA}}}{E_{\mathrm{MCA}}}$	L	L	L	L	L	S	S

Letter 'A', 'B' and 'C' are 'phase A', 'phase B' and 'phase C', respectively. Letter 'G' is ground fault. 'S' represents that Ucosφ is big. 'S' represents that Ucosφ is small.

The transmission line load and phase-to-phase faults identification criterion II is

$$-0.2 < \frac{U_{\mathrm{Mij}}\cos\varphi_{\mathrm{Mij}}}{E_{\mathrm{Mij}}} < 0.5 \tag{14}$$

where ij=AB,BC,CA and $\varphi_{\mathrm{Mij}} = \arg\frac{\dot{U}_{\mathrm{Mij}}}{\dot{I}_{\mathrm{Mij}}} + (90^{\circ} - \varphi_{L1})$.

For phase-to-phase short fault of transmission line, the sensitivity of criterion is bigger than 10 (0.5/0.05). For transmission line load, the sensitivity of criterion is bigger than 1.4 (0.707/0.5).

The relation of criterion I, II and distance protection relay is shown in Figure 8. It can be seen from it that criterion blocks distance protection in load condition and opens it in fault condition of transmission line.

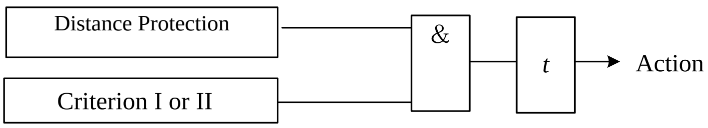

Fig. 8. Operation logic of distance protection and Criterion I and II

IV. SIMULATION

The RTDS simulation system is shown in Figure 9 and transmission line parameters is in Table II. The system can simulate overload and transmission line faults. Distance protection relay 1 is at M side of line MN.

TABLE II. PARAMETERS OF TRANSMISSION LINE (PER 100 KM)

U_n/kV	X_1/Ω	φ_1/(°)	C_1/μF	X_0/Ω	φ_0/(°)	C_0/μF
500	28.0	86.00	1.350	86.0	78.0	0.92
1 000	26.3	88.35	1.397	83.1	79.5	0.93

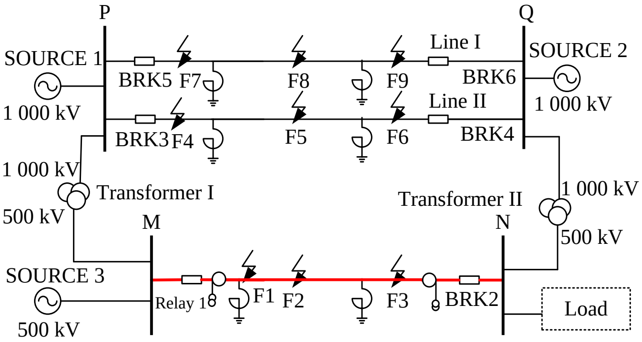

Figure 9. Simulation model

A. External fault during symmetry overload condition

Line MN is in overload condition and phase-A-to-ground fault occurs at F7. The whole process contains two stages, 1) symmetry overload condition of line MN before fault and 2)external fault during symmetry overload condition.

1) Symmetry overload condition of line MN before fault

Table III shows $U\cos\varphi$ of distance relay 1 in symmetry overload condition of line MN before fault. It can be seen from Table III that $\frac{U_{\mathrm{Mi}}\cos\varphi_{\mathrm{Mi}}}{E_{\mathrm{Mi}}}=\frac{U_{\mathrm{Mij}}\cos\varphi_{\mathrm{Mij}}}{E_{\mathrm{Mij}}}=0.8>0.5$,According to criterion I and II, it is overload and blocks distance protection relay 1.

TABLE III UCOSΦ OF SYMMETRY OVERLOAD

$\frac{U_{\mathrm{MA}}\cos\varphi_{\mathrm{MA}}}{E_{\mathrm{MA}}}$	$\frac{U_{\mathrm{MB}}\cos\varphi_{\mathrm{MB}}}{E_{\mathrm{MB}}}$	$\frac{U_{\mathrm{MC}}\cos\varphi_{\mathrm{MC}}}{E_{\mathrm{MC}}}$	$\frac{U_{\mathrm{MAB}}\cos\varphi_{\mathrm{MAB}}}{E_{\mathrm{MAB}}}$	$\frac{U_{\mathrm{MBC}}\cos\varphi_{\mathrm{MBC}}}{E_{\mathrm{MBC}}}$	$\frac{U_{\mathrm{MCA}}\cos\varphi_{\mathrm{MCA}}}{E_{\mathrm{MCA}}}$
0.8	0.8	0.8	0.8	0.8	0.8

2) External fault during overload condition

Table IV shows $\frac{U_{\mathrm{Mi}}\cos\varphi_{\mathrm{Mi}}}{E_{\mathrm{Mi}}}$ of distance relay 1 during external fault. It can be seen from Table IV that $\frac{U_{\mathrm{MA}}\cos\varphi_{\mathrm{MA}}}{E_{\mathrm{MA}}}=0.38<0.5$,According to criterion I, it is a transmission line fault and distance protection relay 1 is opend.

TABLE IV. UCOSΦ OF EXTERNAL FAULT

$\frac{U_{\mathrm{MA}}\cos\varphi_{\mathrm{MA}}}{E_{\mathrm{MA}}}$	$\frac{U_{\mathrm{MB}}\cos\varphi_{\mathrm{MB}}}{E_{\mathrm{MB}}}$	$\frac{U_{\mathrm{MC}}\cos\varphi_{\mathrm{MC}}}{E_{\mathrm{MC}}}$
0.38	0.9	0.9

The measurement impedance of distance relay 1 during external fault is shown in Figure 10, it can be seen that impedances of phase A is out of tripping zone of distance protection relay 1. Distance protection relay 1 will not trip.

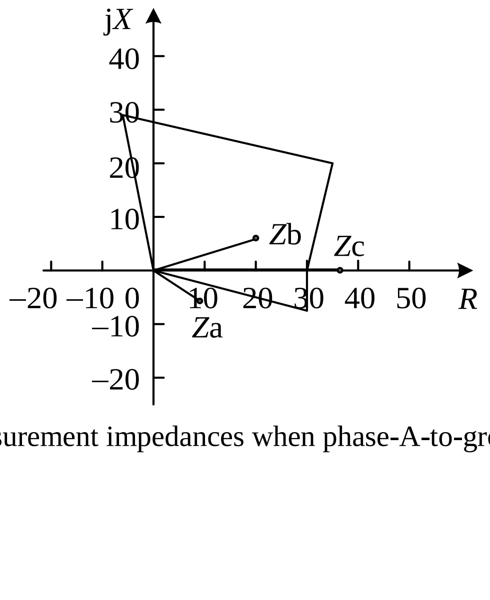

Figure 10. Measurement impedances when phase-A-to-ground fault is at F7

B. Internal Faults during Overload Condition

When phase A break fault occurs in line PQ I, the line MN is in asymmetry overload condition and then phase-A-to-ground occurs at F2 during asymmetry overload condition. It contains two stages, 1) asymmetry overload condition and 2) internal fault during asymmetry overload.

1) Asymmetry overload of line MN before fault

Table V shows $U\cos\phi$ of distance protection relay 1 during asymmetry overload condition. It can be seen from Table V that $\frac{U_{\mathrm{Mi}}\cos\varphi_{\mathrm{Mi}}}{E_{\mathrm{Mi}}}=\frac{U_{\mathrm{Mij}}\cos\varphi_{\mathrm{Mij}}}{E_{\mathrm{Mij}}}=0.92>0.5$ .According to criterion I and II, it is overload and distance protection relay 1is blocked.

TABLE V. UCOSΦ OF ASYMMETRY OVERLOAD

$\frac{U_{\mathrm{MA}}\cos\varphi_{\mathrm{MA}}}{E_{\mathrm{MA}}}$	$\frac{U_{\mathrm{MB}}\cos\varphi_{\mathrm{MB}}}{E_{\mathrm{MB}}}$	$\frac{U_{\mathrm{MC}}\cos\varphi_{\mathrm{MC}}}{E_{\mathrm{MC}}}$	$\frac{U_{\mathrm{MAB}}\cos\varphi_{\mathrm{MAB}}}{E_{\mathrm{MAB}}}$	$\frac{U_{\mathrm{MBC}}\cos\varphi_{\mathrm{MBC}}}{E_{\mathrm{MBC}}}$	$\frac{U_{\mathrm{MCA}}\cos\varphi_{\mathrm{MCA}}}{E_{\mathrm{MCA}}}$
0.92	0.92	0.92	0.92	0.92	0.92

2) Internal fault duding asymmetry overload

Table VI shows $U\cos\phi$ of distance protection relay 1 during internal fault. It can be seen from Table VI that $\frac{U_{\mathrm{MA}}\cos\varphi_{\mathrm{MA}}}{E_{\mathrm{MA}}}=0.23<0.5$. According to criterion I, it is a transmission fault and open the distance protection relay 1.

TABLE VI. UCOSΦ OF INTERNAL FAULT

$\frac{U_{\mathrm{MA}}\cos\varphi_{\mathrm{MA}}}{E_{\mathrm{MA}}}$	$\frac{U_{\mathrm{MB}}\cos\varphi_{\mathrm{MB}}}{E_{\mathrm{MB}}}$	$\frac{U_{\mathrm{MC}}\cos\varphi_{\mathrm{MC}}}{E_{\mathrm{MC}}}$
0.23	0.92	0.85

The measurement impedance of distance relay 1 during internal fault is shown in Figure 11, it can be seen that impedance of phase A is in tripping zone of distance protection relay 1. Distance protection in relay 1 will trip.

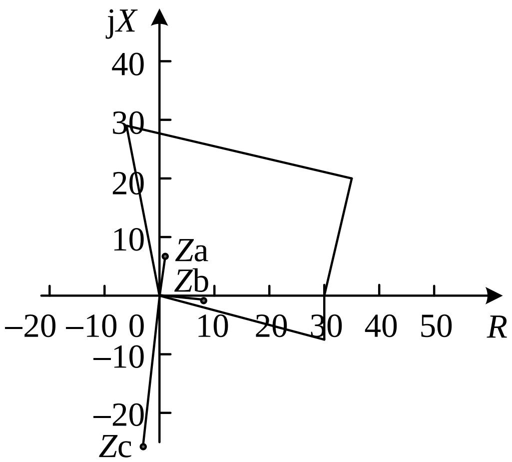

Figure 11. Measurement impedances when phase-A-to-ground fault is at F2

Simulation results show that criterion proposed can identify transmission line overload and faults accurately. It opens distance protection when internal faults and blocks distance protection in overload condition.

V. CONCLUSION

Transmission line overload may cause wrong tripping of distance protection. In this paper, voltage characteristics of transmission line load and faults in voltage plane are analyzed and identification criterion is proposed. $U\cos\varphi$ is used to identify transmission line fault and overload. For overload, the distance protection is blocked. Cascades and blackout caused by distance protection relay wrong tripping in overload condition are stopped.

End of text

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