Smart Power Swing Protection for the Line with Tap

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Smart Power Swing Protection for the Line with Tap

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***Abstract*—Ensuring the selectivity of power swing protection on lines with taps is significantly complicated by the impossibility of measuring the tap power value. The problem is aggravated by the fact that the power of tap varies widely. Usually, known solutions are based on the use of either maximum or average value of the tap power. As a result, both approaches are lack of the optimal solution and lead to a significant narrowing of the protection zone. The article proves that the tap at the protection zone introduces the greatest error in the estimation of the power swing center location if it is located directly near the installation site of the power swing protection. A new method of tap power accounting in the functioning of power swing protection is proposed. It is established that the optimal setting of the power swing protection, which ensures the uniformity of the error in accounting the tap power value in the algorithmic model of the network, is the complex power vector equidistant from the upper and lower boundaries of the tap complex power. The importance of introducing an extended zone into the protection zone is shown, where the power swing protection device operates with a delay.**

Keywords— unstable power swings, power line with the tap, power swing protection

I. INTRODUCTION

The selectivity of the power swing protection (PSP) and, therefore, the success of the elimination of the power swing largely depends on the accuracy of determining the location of the electrical swing center within the protection zone. This requirement is easily met when protecting a power line without a tap. The situation is completely different when protecting power lines with a tap, for example, 110–220 kV power lines. The tap power value varies widely and is inaccessible for measurements, that significantly complicate the task of identifying the swing center in the part of the protection zone located behind the tap point. The wrong choice of power system design modes leads either to unwanted tripping of the PSP when the swing center is located outside the protection zone or PSP malfunctioning when the swing center in the protection zone.

The task of considering the influence of a tap on the functioning of PSP has long been known [1] and [2], in the technical and scientific literature describes many different ways to solving it. For example, in various working and repair schemes, it is proposed to select the averaged settings for PSP. The success of this approach largely depends on the professional qualities of a technical specialist, and therefore often the decisions are far from optimal. Often in the calculations, it is invited to consider a tap with their maximum power [3]. However, such a solution decreases the PSP device sensitivity, leading to a significant narrowing of the protection zone and, consequently, the appearance of a dead zone in determining the location of the swing center.

This report suggests a method for accounting a tap of 110-220 kV lines in PSP settings, which is optimal for the criterion of the accuracy of determining the location of the swing center in the protection zone. The relevance of the topic is dictated, first of all, by the wide use of PSP devices for 110-220 kV lines with a tap.

II. THE CONDITION OF MAXIMUM ERROR OF POWER SWING PROTECTION

Let us determine the location of the tap in line relative to the installation location of the PSP device (Fig. 1 the installation place of the PSP device is indicated by a flag), at which there will be a maximum PSP error. Electrical systems on both sides of the protection line are represented by equivalent EMF $\underline{E}_1$ and $\underline{E}_2$ with internal resistances $\underline{Z}_{s1}$ and $\underline{Z}_{s2}$ [3] - [5]. For the convenience of presentation, the relative values of the EMF are used, assuming that they vary in the range 0.9 ÷ 1.1 of the nominal value [7] - [9]; then

$$\underline{E}_2 = q\underline{E}_1 e^{-j\delta}, \tag{1}$$

where δ is the transmission angle, $q \in [0.82;1.22]$. The PSP device is installed at the beginning of the line (from the EMF side $\underline{E}_1$) and protect the power transmission line with complex resistance $\underline{Z}_L = z_L e^{j\varphi_L}$, the electrical distance to tap point (the point of connecting the tap with complex resistance $\underline{Z}_b = z_b e^{j\varphi_b}$) is set by the coefficient γ. The tap is characterized by a constant complex power $\underline{S}_b$ in the power swing in the range from minimum $\underline{S}_{b,\min} = 0$ to maximum value $\underline{S}_{b,\max} = S_{b,\max} e^{j\varphi_b}$, where φ_b also varies in the range from $\varphi_{b,\min}$ to $\varphi_{b,\max}$.

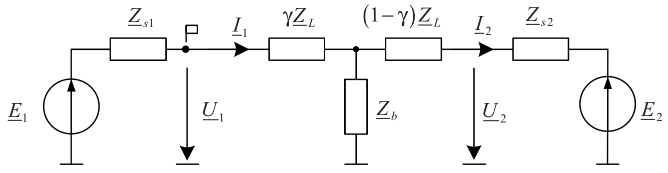

Fig. 1. The swing center scheme of the electrical network with a tap

The PSP device measures the angle between the voltage at the installation location and the voltage estimation at the end of the protected zone (in our case, at the opposite end of the line)

$$\hat{\underline{U}}_2 = \underline{U}_1 - \gamma\underline{Z}_L\underline{I}_1 - (1-\gamma)\underline{Z}_L\hat{\underline{I}}_2. \tag{2}$$

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There is an uncertainty in the voltage estimation $\hat{\underline{U}}_2$ due to the unknown load value $\underline{Z}_b$. It is usually resolved by setting a fixed load power $\underline{S}_{b,\text{set}}$ in the PSP settings. The setting value of the load resistance in the PSP is calculated using the nominal value of the voltage U_{nom}

$$\underline{Z}_{b,\text{set}} = \frac{U^2_{\text{nom}}}{S_{b,\text{set}}} e^{j\varphi_{b,\text{set}}}. \qquad (3)$$

Then the current estimation for the section of the line behind the tap in the PSP is calculated as follows

$$\hat{\underline{I}}_2 = \underline{I}_1\left(1+\gamma\frac{\underline{Z}_L}{\underline{Z}_{b,\text{set}}}\right) - \underline{U}_1\frac{1}{\underline{Z}_{b,\text{set}}}. \qquad (4)$$

The accepted assumption expressed as an estimation (4), leads to an error in the estimation of the voltage at the end of the protection zone $\hat{\underline{U}}_2$. Using estimations (2) and (4) and following the network scheme (Fig. 1), the error of the voltage estimation $\underline{U}_2$ can be expressed as

$$\begin{aligned}\Delta\underline{U}_2 &= \underline{U}_2 - \hat{\underline{U}}_2 = (1-\gamma)\underline{Z}_L\left(\hat{\underline{I}}_2 - \underline{I}_2\right) = \\ &= (1-\gamma)\underline{Z}_L(\underline{U}_1 - \gamma\underline{Z}_L\underline{I}_1)\left(\frac{1}{\underline{Z}_{b,\text{set}}} - \frac{1}{\underline{Z}_b}\right).\end{aligned} \qquad (5)$$

And, as can be seen from the diagram (Fig. 2), it is the shift of the estimation vector $\hat{\underline{U}}_2$ relative to the voltage vector $\underline{U}_2$ that determines the angular error of the PSP $\Delta\delta_c$, and its value depends on the error vector $\Delta\underline{U}_2$ and its position.

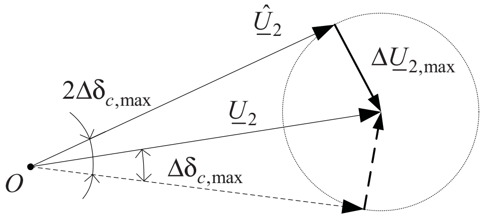


Fig. 2. Diagram illustrating the relationship of the error in the angle estimation with the error in the voltage estimation vector

Let's denote the miss in the assignment of load admittance as

$$\Delta\underline{Y}_b = \frac{1}{\underline{Z}_b} - \frac{1}{\underline{Z}_{b,\text{set}}}. \qquad (6)$$

Now it can be seen from expression (5) that the error $\Delta\underline{U}_2$ in the voltage estimating at the opposite end of the protection zone $\underline{U}_2$ is directly proportional to the value of the miss $\Delta\underline{Y}_b$ (6) and reaches the maximum value $\Delta\underline{U}_{2,\max}$ when the load point is located near the PSP device installation place, that is when $\gamma = 0$.

III. Optimal Power Swing Protection Setting

As follows from expressions (5) and (6), the minimum error in the voltage estimation $\hat{\underline{U}}_2$ is achieved when the norm of the miss vector $\Delta\underline{Y}_b$ is reduced

$$\Delta Y_b = \frac{\Delta S_b}{U^2_{\text{nom}}} \to \min, \qquad (7)$$

where ΔS_b is the absolute value of the mismatch vector between the load power and the setting

$$\Delta\underline{S}_b = S_b e^{j\varphi_b} - S_{b,set} e^{j\varphi_{b,set}}. \qquad (8)$$

To meet the optimality condition (7), it is necessary to ensure that the value ΔS_b is minimal for any of the possible vectors $\underline{S}_b$ over the entire range of changes in the load power $\underline{S}_b$.

It is convenient to analyze the rules for fulfilling the optimality condition (7) on the complex plane with coordinate axes P and jQ (Fig. 3). It is intuitively clear that the end of the setting of the power vector $\underline{S}_{b,set}$ should lie in the center O_1 of the circle, describing the area of change in load power outlined by the *A*–*B*–*O* sector. The characteristic parameters of the setting will be as follows: absolute value

$$S_{b,set} = \frac{S_{b,\max}}{2\cos\left(\dfrac{\varphi_{b,\max} - \varphi_{b,\min}}{2}\right)} \qquad (9)$$

and the argument

$$\varphi_{b,set} = \frac{1}{2}\left(\varphi_{b,\max} + \varphi_{b,\min}\right). \qquad (10)$$

Then the impedance setting of PSP for the line model with tap is determined by (3).

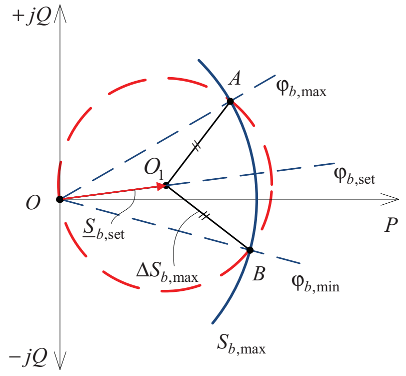


Fig. 3. The rule of setting power $\underline{S}_{b,set}$ choice

IV. DEVIATION OF ESTIMATION OF SWING CENTER LOCATION

The selection $\underline{S}_{b,\text{set}}\left(\underline{Z}_{b,\text{set}}\right)$ does not completely exclude the PSP error, but only determines the minimum angular error condition. Therefore, it is important to estimate the effect of a tap on the accuracy of determining the swing center.

It is clear that if the tap power coincides with the PSP setting the swing center location will be determined accurately. But any deviation of the load parameters from the setting (2) will lead either to a narrowing of the PSP protection zone or to its expansion. To ensure the correct functioning of the PSP, it is important to know the deviation range of the protection zone, i.e. the limits of changes in the areas of expansion and narrowing of the areas. Further, the main regularities characterizing the mentioned areas in the regime of maximum error are presented $(\gamma = 0)$.

We will assume that an unstable power swing is detected based on the angle $\delta_c = \arg\left(\underline{U}_1\right) - \arg\left(\hat{\underline{U}}_2\right)$ exceeding the critical value equal to 180°. Due to inconsistent accounting of the tap power (due to $\Delta\underline{S}_b \neq 0$ in expression (8)), the voltage vector at the end of the protection zone $\underline{U}_2$ and the vector of its estimation $\hat{\underline{U}}_2$ do not coincide, so the PSP will identify the start of unstable power swing depending on the slip sign either before the angle $\delta_{sc,\nu}$ between $\underline{E}_1$ and $\underline{E}_2$ reaches 180°, or later when it turns out that $\delta_{sc,\nu} > 180^{\circ}$.

Angle monitoring is equivalent to the impedance tracking

$$\hat{\underline{Z}}_R(\delta) = \frac{\underline{U}_1}{\hat{\underline{I}}_2}. \tag{11}$$

Equality $\delta_c = 180^{\circ}$ means that in the measurement basis (11), the trajectory of the impedance estimation $\hat{\underline{Z}}_R(\delta)$ intersects the vector $\underline{Z}_L$ at $\delta = \delta_{sc,\nu}$.

The difference between the setting $\underline{S}_{b,\text{set}}\left(\underline{Z}_{b,\text{set}}\right)$ and $\underline{S}_b\left(\underline{Z}_b\right)$ leads to a shift in the estimation of the swing center location, creating conditions under which the swing center outside the protection zone will be accepted by the PSP as internal, forming narrowing area of the protection zone, and vice versa, the swing center in the protection zone – as external, forming an expansion area of the protection zone (Fig. 4). In both cases, the PSP functioning will be incorrect: in the first case, it will falsely divide the network, and in the second – it will unduly malfunction. To avoid PSP malfunctioning, the protection zone should be divided into two sections: the main and extended zones. If we suppose that the PSP border zone is located at the end of the power line, the main zone extends from the PSP installed place to the lower limit point of the narrowing area $\underline{Z}_L(1-\varepsilon_-)$; on it, the PSP unmistakably determines the swing center location in the protection zone and can give an action signal without delay. The extended zone includes both the narrowing area $\underline{Z}_L\varepsilon_-$ and the expansion area $\underline{Z}_L\varepsilon_+$. On it, the PSP can not distinguish the internal swing center from external, and therefore must function with a delay necessary for the PSP device action at the opposite side of the power line, which is in a more advantageous position in terms of accuracy. Here ε_- and ε_+ are the relative lengths of the narrowing and expanding areas.

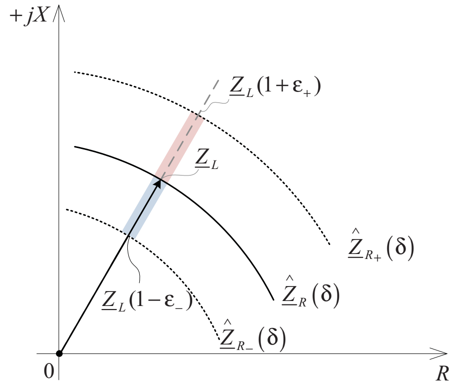


Fig. 4. Expansion area and narrowing area (upper and lower colored segments on the continuation of the vector $\underline{Z}_L$) of the PSP protection zone

Following Fig. 4, estimate the values of ε_- and ε_+ as:

$$\varepsilon_- = 1 - \frac{\hat{\underline{Z}}_{R-}\left(\delta_{sc,\nu}\right)}{\underline{Z}_L} \tag{12}$$

and

$$\varepsilon_+ = \frac{\hat{\underline{Z}}_{R+}\left(\delta_{sc,\nu}\right)}{\underline{Z}_L} - 1, \tag{13}$$

цhere $\hat{\underline{Z}}_{R-}(\delta)$ and $\hat{\underline{Z}}_{R+}(\delta)$ – the trajectory of impedance estimation that forms the limit points of the narrowing area and expansion area.

Remind that at the angle $\delta = \delta_{sc,\nu}$ between the sources $\underline{E}_1$ and $\underline{E}_2$ the trajectory $\hat{\underline{Z}}_{R-}(\delta)$ and $\hat{\underline{Z}}_{R+}(\delta)$ intersect the line on which the vector $\underline{Z}_L$ lies.

In general, the border of the narrowing and expanding area are reached at the tap parameters $\underline{S}_b(\underline{Z}_b)$ corresponding to the coordinates of points *A, B,* and 0 (Fig. 3).

Obviously, the largest size of the area of narrowing and expansion of the protection zone is reached when the swing center is at the end of the power line. In this case, there is a relationship between the impedances of the systems on the left and the right:

$$\underline{Z}_{s2} = qe^{j(\pi-\delta_{sc,r})}\left[\underline{Z}_L + \underline{Z}_{s1}\left(1 + \frac{\underline{Z}_L}{\underline{Z}_b}\right)\right], \tag{14}$$

and the transmission angle corresponding to the moment of occurrence of swing center on the power line will be equal to

$$\delta_{sc,r} = \frac{\pi}{2} + \arg\left[\underline{Z}_L + \underline{Z}_{s1}\left(1+\frac{\underline{Z}_L}{\underline{Z}_b}\right)\right]. \qquad (15)$$

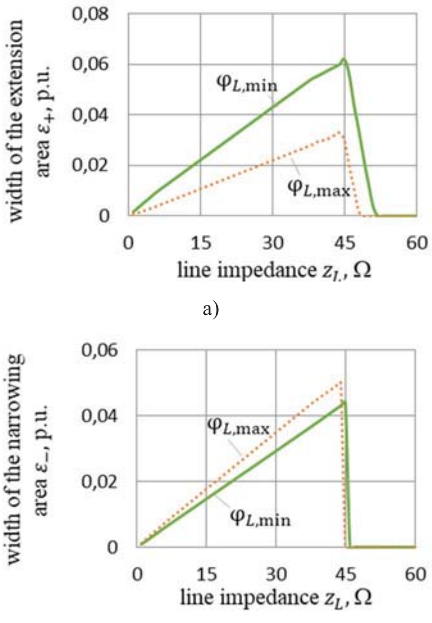
To estimate the values ε_- and ε_+ use the impedance estimation defined with (5) at the angle $\delta_{sc,\nu}$,

$$\hat{\underline{Z}}_R\left(\delta_{sc,\nu}\right) = \frac{1}{\Delta\underline{Y}_b + \dfrac{1-qe^{-j\delta_{sc,\nu}}\left(1+\dfrac{\underline{Z}_{s1}}{\underline{Z}_b}\right)}{\underline{Z}_L+\underline{Z}_{s2}+q\underline{Z}_{s1}e^{-j\delta_{sc,\nu}}}}. \qquad (16)$$

The calculation procedure will be as follows. First, the impedance $\underline{Z}_{s2}$ is calculated using the expression (15). Then the transcendental equation is solved

$$\arg\left[\hat{\underline{Z}}_R\left(\delta_{sc,\nu}\right)\right] = \arg(\underline{Z}_L) \qquad (17)$$

relative to $\delta_{sc,\nu}$ and using expressions (12) and (13), the desired values ε_- and ε_+ determined for changing parameters of 110 and 220 kV networks in the entire possible range of their changes [10] and [11]. The calculation results are shown in Fig. 5 for line 110 kV at the minimum $\varphi_{L,\min} = 46^\circ$ and maximum $\varphi_{L,\max} = 74^\circ$ line angles and in Fig. 6 for line 220 kV at the minimum $\varphi_{L,\min} = 74^\circ$ and maximum $\varphi_{L,\max} = 82^\circ$ line angles.



a)

b)

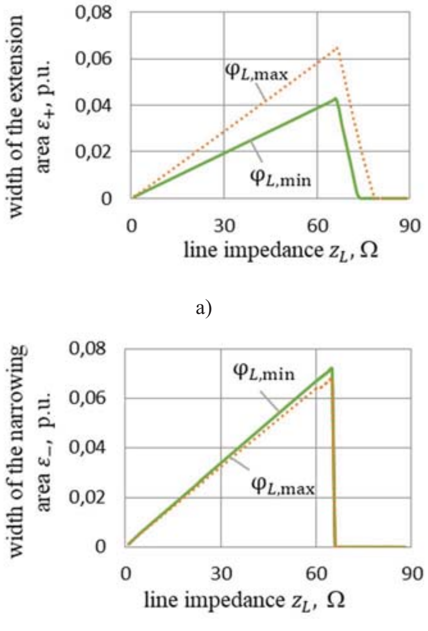
Fig. 5. Width of the expansion area ε_+ (a) and narrowing area ε_- (b) of the protection zone for line 110 kV

Calculations show that the maximum size of the areas of narrowing ε_- and expansion ε_+ increases with the length (impedance z_L) of the line (Fig. 5, Fig. 6), which, of course, will require increases in the extended zone of the PSP. However, at a certain length (impedance z_L) of the line, all possible swing center will be located inside the protection zone, so the width of the areas of narrowing ε_- and expansion ε_+ after reaching its maximum begins to decrease until it disappears. In other words, the need to introduce an extended zone exists only for relatively short lines.

Interestingly, the angle of the line φ_L has a significant effect on the size of the expansion area and almost no effect on the size of the narrowing area.

V. CONCLUSIONS

Tap on the protection zone makes the greatest error in the estimation of the swing center location in the case of tap location directly near the installation place of the PSP device. The optimal setting of the PSP is the complex power vector, wich equidistant from the upper and lower boundaries of the tap complex power. The optimal tap power setting ensures the estimation of the swing center location with an accuracy of more than 7% of the line length with the tap power equals to 50% of the transmitted power. The importance of introducing an extended zone into the protection zone of the PSP device in which the device operates with delay is shown. It was found that for sufficiently long lines (for high line impedance) there is no need to introduce an extended zone since in this case, all swing center is internal.



a)

b)

Fig. 6. Width of the expansion area ε_+ (a) and narrowing area ε_- (b) of the protection zone for line 220 kV

REFERENCES

[1] V.G. Narovlyansky, A.B. Vaganov, I. A. Ivanov "Test results of the device for power swing protection ALAR-M". Relay protection and automation. No. 1 (01). 2010.

[2] M.I. Alexandrova, V.I. Antonov, V.A. Naumov, V.S. Petrov "Fundamentals of the choice of settings for power swing protection in multi-link electrical networks". Information technologies in electrical engineering and electric power industry: materials of the XI All-Russian scientific and technical conference. Cheboksary: Publishing house of the Chuvash University, 2018. P. 254 – 257.

[3] V. Sushko, A. Podshivalin "Power transmission lines with a tap. Features of setting up PSP devices". News of Electrical Engineering, no. 5 (65). 2010. P. 40 – 44.

[4] A. Marusic, S. Skok and I. Marusic, "Power system blackout prevention using pole slip protection on 400 kV transmission line," 2005 International Conference on Future Power Systems, Amsterdam, 2005, pp. 4, doi: 10.1109/FPS.2005.204243.

[5] J. Blumswing center hein, Y. Yelgin and M. Kereit "Proper detection and treatment of power swing to reduce the risk of blackouts", 2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, Nanjing, 2008, pp. 2440-2446, doi: 10.1109/DRPT.2008.4523821.

[6] Emergency automation of power systems: product catalog. R&P EKRA Ltd., 8th edition, 2018. 68 p.

[7] Power swing and out-of-step consideration on transmission lines: a report to the Power System Relaying Committee. Of the IEEE Power Engineering Society, 2005. – 59 p.

[8] V.I. Antonov, V.A. Naumov, V.S. Petrov, M.I. Alexandrova, A.N. Nikitina "The choice of the characteristics of the function for the power swing elimination". Information technologies in electrical engineering and power engineering: materials of the X Russian scientific and technical conference. Cheboksary: Publishing house of the Chuvash University, 2018, pp. 225–228.

[9] Ya.E. Gonik, Ya.E. Iglitskiy Power swing protection. Moscow: Energoatomizdat, 1988. 112 p.

[10] V.I. Idelchik Power systems. Moscow: Energoatomizdat. 1989. 592 p.

[11] A.N. Nikitina, V.S. Petrov, V.A. Naumov, V.I Antonov "The optimum setting of power swing protection for power line with branch". Relay protection and automation. 2020, № 2. P. 39 – 45.

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