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QUESTION N° : 1.05

Power-swing characteristics in lower inertia grid

1 Introduction

In paper No. 1.05, the authors discussed on how the critical clearance time (CCT) of a synchronous machine is affected by replacing the SMIB model by a two-machine model, in which the second machine has variable inertia H_{EQ}, representing a power grid. This is important for setting protection relays, such as distance protection, which calculates the “impedance seen by the relay” by monitoring voltage and current. Once a fault occurs, the voltage drops and the current increases, meaning that the calculated impedance decreases. If the fault is in the protected line segment, the calculated impedance promptly jumps into the protective zone in the complex plane, causing a trip.

The calculated impedance is also affected by power swings, during which distance relay should avoid tripping. The relay needs to distinguish between faults and power swings. This contribution explains how power swings characteristics is impacted by decreased network inertia, affecting the impedance seen by the relay.

2 Background

Let us consider a two-machine model (Fig. 1). The machines are modelled as a voltage source behind a transient impedance ($\underline{Z}_A$ and $\underline{Z}_B$ correspond to the machines G_A and G_B, respectively). The angle reference is set to machine G_B (representing a network) and phase angle difference between both voltages equals δ. During power swings, δ changes according to swing equations of individual machines. Line with an impedance $\underline{Z}_L$ connects both machines.

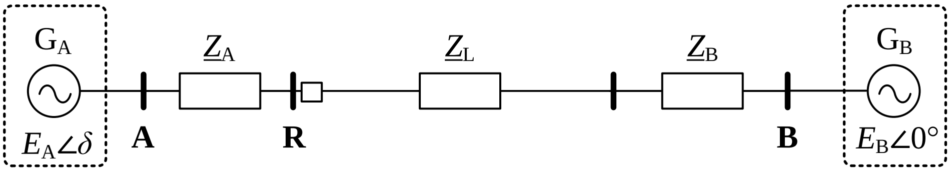

Fig. 1: A two-machine model

The total impedance between both machines equals:

$$\underline{Z}_T = \underline{Z}_A + \underline{Z}_L + \underline{Z}_B \tag{1}$$

and the relay is located at the beginning of a line (R point), facing towards G_B. The relay sees the impedance $\underline{Z}_R$:

$$\begin{aligned} \underline{Z}_R &= \frac{\underline{U}_R}{\underline{I}_R} = \frac{\underline{E}_A - \underline{I}_R \cdot \underline{Z}_A}{\underline{I}_R} = \frac{\underline{E}_A}{\underline{I}_R} - \underline{Z}_A \\ \underline{I}_R &= \frac{\underline{E}_A - \underline{E}_B}{\underline{Z}_T} \end{aligned} , \tag{2}$$

where $\underline{U}_R$ and $\underline{I}_R$ are voltage and current applied to the relay. By expressing the ratio between internal voltage amplitudes of machines as:

$$\frac{|\underline{E}_A|}{|\underline{E}_B|} = K , \tag{3}$$

we can derive the impedance $\underline{Z}_R$ as a function of two variables:

$$
\underline{Z}_{\mathrm{R}}\left(K,\delta\right)=\frac{\underline{E}_{\mathrm{A}}}{\underline{I}_{\mathrm{R}}}-\underline{Z}_{\mathrm{A}}=\frac{\underline{E}_{\mathrm{A}}}{\underline{E}_{\mathrm{A}}-\underline{E}_{\mathrm{B}}}\cdot\underline{Z}_{\mathrm{T}}-\underline{Z}_{\mathrm{A}}=\frac{K\cdot\left|\underline{E}_{\mathrm{B}}\right|\cdot e^{j\delta}}{K\cdot\left|\underline{E}_{\mathrm{B}}\right|\cdot e^{j\delta}-\left|\underline{E}_{\mathrm{B}}\right|\cdot e^{j0}}\cdot\underline{Z}_{\mathrm{T}}-\underline{Z}_{\mathrm{A}}=
$$
$$
=\frac{K\cdot e^{j\delta}}{K\cdot e^{j\delta}-1}\cdot\underline{Z}_{\mathrm{T}}-\underline{Z}_{\mathrm{A}} \quad . \qquad (4)
$$

Let us study $\underline{Z}_{\mathrm{R}}$ (K, δ) by manipulating δ and K. *Firstly*, we consider K as a parameter (ranging from 0.5 to 1.5) and vary δ from 0° to 360°. This generates a set of circular blue curves (Fig. 2a), meaning that at a certain K, impedance $\underline{Z}_{\mathrm{R}}$ will follow one of these curves once there is a power swing present. *Secondly*, we consider δ as a parameter (ranging from 90° to 270°) and vary K in an unreasonably wide range. We get a set of circular yellow curves, which intersect in two locations A and B, corresponding to electrical distances from the relay location R to both machines. With solid black lines in Fig. 2a, individual impedances $\underline{Z}_{\mathrm{A}}$, $\underline{Z}_{\mathrm{L}}$ and $\underline{Z}_{\mathrm{B}}$ are plotted. A black dot in the first quadrant represents an impedance between relay point R and machine B, whereas a black dot in the third quadrant represents an impedance between relay point R and machine A.

Not the entire swing impedance chart is of importance during a power swing since variations in network voltages are limited. Therefore, we are interested in observing only a certain portion of curves, presented in Fig. 2b, corresponding to values K between 0.9 and 1.1. For angles in the range ± 60° (normal operation, blue colour), $\underline{Z}_{\mathrm{R}}$ is far from the complex diagram origin, around which mho characteristic is placed. However, during power swings, $\underline{Z}_{\mathrm{R}}$ approaches the origin. For stable power swings, angle ranges between 60°-120° (and 240°-300° in the opposite direction, yellow colour). Unstable swings (angle range between 120° and 240°, red colour) bring $\underline{Z}_{\mathrm{R}}$ in the very heart of the diagram.

The idea behind a power swing blocking function of a distance/out-of-step relay is to differentiate between causes that bring the impedance within the protective zone. When this happens due to a fault, much faster impedance changes occur compared to conditions that arise from power swings. A typical out-of-step relay characteristics are shown in Fig. 3 (either two concentric impedance circles or straight lines). The outer zone is used to start a timer. If the inner zone is never entered, a *stable swing* is assumed. The *unstable swing* is declared if the inner zone is reached before the timer runs out. If both zones are entered very quickly, a *fault* is declared.

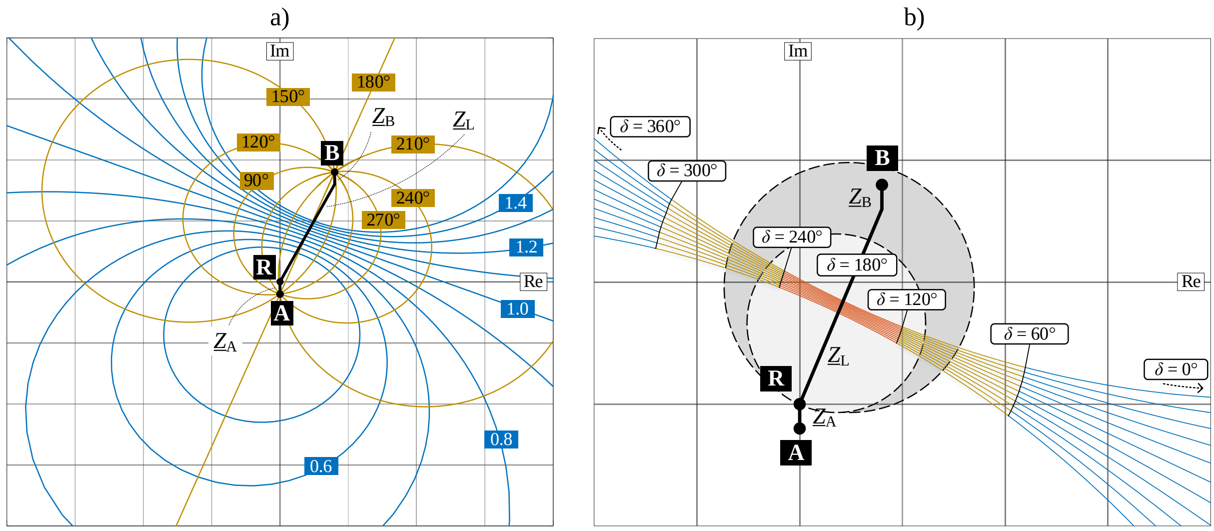

Fig. 2: A swing impedance chart (a) and impedance trajectories during a power swing (b)

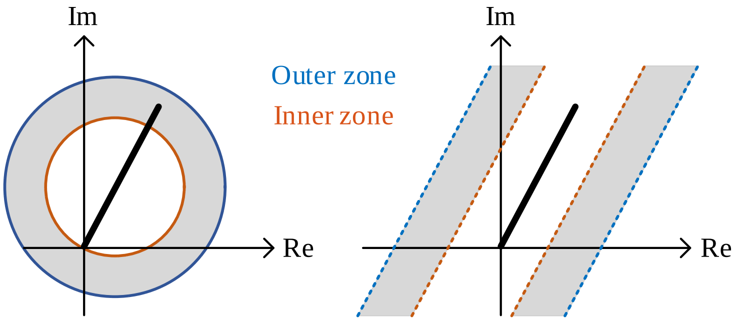

Fig. 3: Inner and outer zones for detecting power swing condition [1]

3 Impact of decreased system inertia

In Fig. 4a, two angle swings are presented that correspond to simulation results from paper 10622 (B5-PS1) (SL) with H_{EQ} = 10 sec and H_{EQ} = 100 sec. As already concluded in the paper, lower H_{EQ} causes longer CCTs. However, the paper did not sufficiently stress that this makes critical clearance angle δ_C and maximal angle δ_m to increase as well. At the same time, the swing duration T_S (the time from fault occurrence to angle reaching δ_m) remains unchanged – see dashed black (result for individual H_{EQ}) and solid black curves (mean value for the entire H_{EQ} span) in Fig. 4b. A reason for the variations in T_S in Fig. 4b lies in a difficulty in finding a peak of an almost flattened angle curve (see Fig. 4a). From Fig. 4a one can observe that decreased H_{EQ} causes slower acceleration of δ and offers more decelerating energy after fault clearing. This is confirmed in paper 10622 (Fig. 7), depicting equal-area criterion in a decreased inertia environment.

4 Conclusions

In this contribution, we stressed that in a reduced inertia environment, an increase in critical clearance and maximum angles can be expected, of which the latter will affect power swings characteristics. This might be a reason for necessary changes in power swing blocking characteristic in terms of outer and inner-zones placement. Since the time for reaching the maximum angle remains unaltered, the corresponding timers can be kept unchanged.

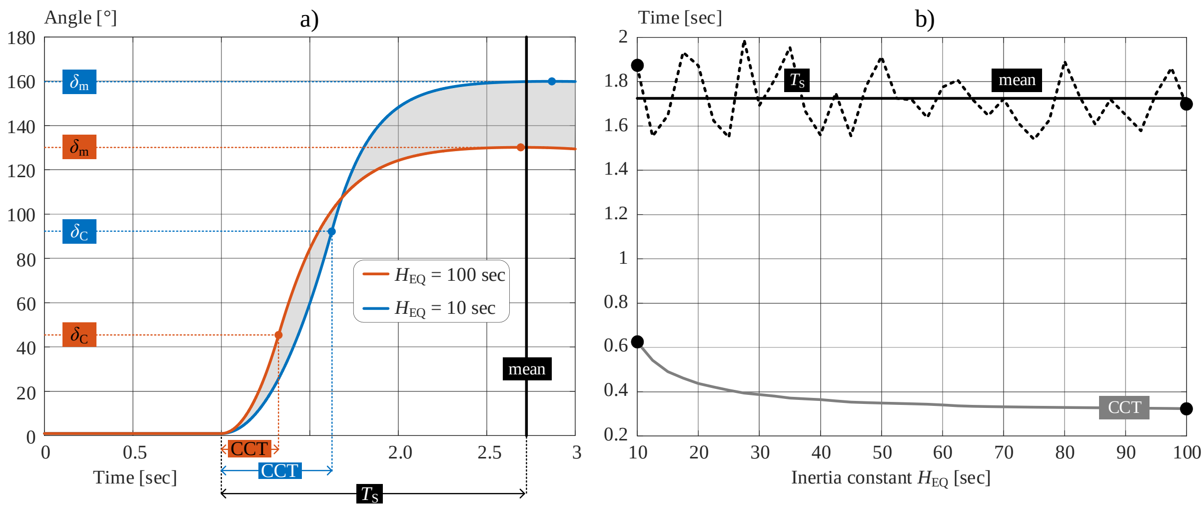

Fig. 4: Angle swing in a time domain (a) and duration of a stabile swing (b)

5 Literature

[1] S. H. Horowitz and A. G. Phadke, *Power system relaying*, Fourth edition. Chichester, West Sussex, United Kingdom: Wiley, 2014.