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Concept of Smart ACR Setting in Real-Time Operation of Power Systems

***Abstract**. The automatic circuit recloser (ACR) plays an essential role in the operation of not only the transmission, but also the distribution systems, where it helps to restore normal system operation after a failure, the correct setting of which is very important, especially in terms of transient stability of generators and power system stability as a whole. In this paper, we deal with the correct setting of the ACR cycle based on data from the real operation of the power system and its incorporation into the operational management of the power system.*

***Streszczenie.** Automatyczny reklozer (ACR) pełni istotną rolę w pracy nie tylko przekładni, ale również systemów rozdzielczych, gdzie pomaga przywrócić normalną pracę systemu po awarii, której prawidłowe ustawienie jest bardzo ważne, zwłaszcza w zakresie stabilności przejściowej generatorów i stabilności systemu elektroenergetycznego en bloc. W niniejszym artykule zajmujemy się prawidłowym ustawieniem cyklu ACR na podstawie danych z rzeczywistej pracy systemu elektroenergetycznego i jego włączeniem do zarządzania operacyjnego systemem elektroenergetycznym. (**Koncepcja inteligentnego ustawiania ACR w pracy systemów elektroenergetycznych w czasie rzeczywistym**)*

Keywords: Automatic circuit recloser, transient stability, synchronous generator, overhead lines, power system, short-circuit.
Słowa kluczowe: Automatyczny reklozer, stabilność przejściowa, generator synchroniczny, linie napowietrzne, system elektroenergetyczny, zwarcie.

Introduction

In recent years, ACR has become an important tool to increase the stability of the power system, as it helps to restore normal operating state after a temporary failure, such as short-circuits or earth faults. The use of ACR in transmission and distribution networks also increases the reliability of the electricity supply to customers. Approximately 80% of all faults on overhead lines are temporary single-phase earth faults [7], in which the use of ACR is at most effective. However, reclosing the remaining 20% of outages might represent a serious risk to power system stability. Therefore, it is necessary to be able to distinguish between transient and long-term faults on the transmission lines.

However, it should be noted that short-circuits and earth faults on overhead lines are usually accompanied by arcing, either primary (occurs after a fault and burns until affected phases are disconnected) or secondary (this occurs after the circuit breakers are switched off in response to capacitive and inductive coupling between healthy and damaged phases) [8] and it is the presence of the secondary arc that has a significant effect on the success of single-phase ACR cycles. In the case of three-phase faults, the secondary arc does not arise. The extinction time of the secondary arc can be determined according to [9] and [10] based on the analysis of the values of harmonic outage currents and voltages generated during the secondary arc. On the contrary, [11] describes the moment of extinguishing the secondary arc using the RMS values of the voltages of the open phases. Other methods are described in [12], [13], [14], [15]. Therefore, knowing the moment of arc burn-up and deionization of the surrounding space is extremely important in terms of power system stability.

By analyzing the dependence of the active power of the generator on the rotor angle (P = f (δ)), we can conclude that a successful ACR cycle has a positive effect on the transient stability of synchronous generators and thus the stability of the whole power system. To demonstrate this positive effect, it is possible to use the equal area method by applying it to a simple model OMIB (One Machine Infinite Bus). With a successful ACR, the deceleration area increases; conversely, the unsuccessful ACR cycle has a negative effect due to the increase of the acceleration area. The acceleration and deceleration areas are represented in Fig. 2 (curve I – state before fault, II – state of short-circuit, III – state after fault). The shift of operation point from A to B is moment of short-circuit, section BC is short-circuit duration, the power line was switched off at point C, section C-D represents single line operation, and at the point E the power line was switched on. On the left side of Fig. 2 a successful ACR is being represented, i.e., the fault was temporary, and the line remains in operation, on the right the ACR is unsuccessful, i.e., the line was short-circuited again (shift of operation point to curve II).

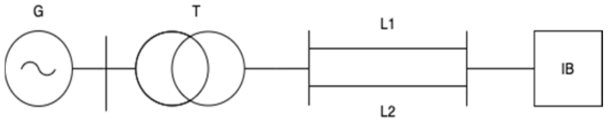


Fig.1. Model OMIB - One Machine Infinite Bus

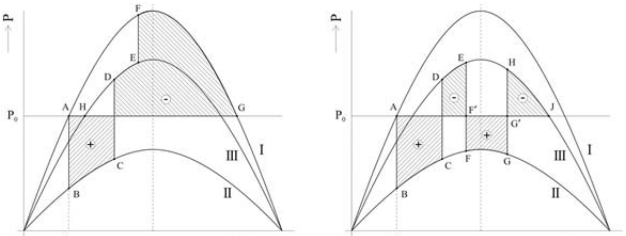


Fig.2. Comparison of accelerating and braking areas at successful and unsuccessful ACR [1]

From the point of view of transient stability as well as from the point of view of the end of the transient fault (arc burn-up), the time setting of the ACR is important, specifically the duration of the dead time. In the literature, we can find its minimum recommended values [2] depending on the nominal voltage of the line on which the ACR is operated:

- 66 kV line - 0.2 s
- 110 kV line - 0.28 s
- 132 kV line - 0.3 s
- 220 kV line - 0.35 s
- 275 kV line - 0.38 s
- 400 kV line - 0.45 s

- 525 kV line - 0.55 s

However, fixed dead times do not respond to the requirements of modern power systems, as these settings do not consider the operating state, network configuration, and power sources connection. In general, we can say that the length of the dead time must be set with respect to the state and configuration of the network before the fault, the type, severity of the fault, and the moment of burnout of the arc.

Based on the above, several algorithms were developed using operative control of the dead time length, e.g. using neural networks [16,17]. The problem with the use of neural networks is the fact that they require a large amount of data on which the algorithm is configured.

Swing equation of the generator

For a correct understanding and application of adaptive smart ACR, it is necessary to analyze the swing equation of the generator. Since the transient stability of the synchronous generator is usually lost during the first swing period, the damping effect can be neglected. The swing equation of the generator can be written in the form

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2}=\frac{P_m-P_e}{S_{rg}} \tag{1}$$

where: H – inertia constant [MW.s/MVA], ω_0 – nominal angular speed [rad.s^{-1}], δ – rotor angle [rad], P_m – input mechanical power [MW], P_e – output electrical power [MW], S_{rg} – rated generator power [MVA].

The output electrical power of the generator, if the rotor type is neglected, is defined as

$$P_e=\frac{EU}{X}\sin\delta \tag{2}$$

where: E – electromotive force of the generator [kV], U - terminal voltage of the generator, (respectively, voltage on the busbar, where the generator is connected to the power system) [kV], X - total system reactance (reactance of the generator, transformer, line and short-circuit reactance of the net) [W]

Since the parameters H, S_{rg}, Pm and ω_0 in the swing equation (1) are constant, the acceleration of the rotor, the speed of the rotor, the angle of the rotor, and the output electrical power continuously change with time, this fact can be seen in the graphs below (Fig.4 and Fig.5.), if we look at the processes after the end of ACR.

Influence of selected parameters of the ACR cycle setting on the generator stability

The ACR cycle is defined by the following parameters:

- the circuit breaker switch-off speed,
- the dead time length,
- the circuit breaker switch-on speed,
- number of failed cycles.

A. Circuit breaker switch-off speed

The line shutdown speed is limited by the technical capabilities of the circuit breaker, the speed of fault detection, and by sending a shutdown command to the circuit breaker.

Table 1. shows the individual response times of the tripping cycle depending on the type of circuit breaker and the voltage level [2]. In general, the fault (short-circuit) detected by the first protection zone is switched off immediately because of the thermal effects of the short-circuit current. The greatest force effects of the short-circuit current occur in the first half -period since the short-circuit occurs, and the thermal effects depend on the duration of the short-circuit.

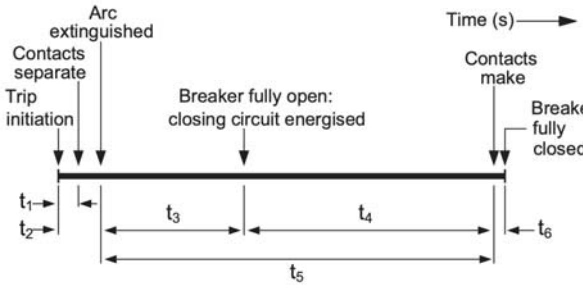


Fig. 3. Operation cycle of a circuit breaker [2]

Table 1. Typical values of circuit-breaker tripping cycle times [2]

	Oil 11 kV	Vacuum 15 kV	Oil 132 kV	Air 380 kV	SF6 132 kV	SF6 380 kV
t_1	0.06	0.038	0.03	0.035	0.04	0.02
t_2	0.10	0.053	0.06	0.045	0.07	0.05
t_3	0.08	0.023	0.20	0.235	0.03	0.01
t_4	0.16	0.048	0.35	0.065	0.08	0.06
t_5	0.24	0.280	0.55	0.300	0.11	0.07
t_6	0.02	0.070	0.01	0.020	0.12	0.04

Therefore, if the situation allows, i.e. the devices have sufficient short-circuit resistance to the thermal effects of the short-circuit current, it is possible to extend the line shutdown time after a failed ACR. The effect of such a shift is shown in Fig. 4. It can be seen from the waveforms that the amplitude of the angle d change increases with a delayed short-circuit; this dependence is shown in the last graph of Fig. 4. The exponential character of the course is caused by the increasing speed of the generator rotor due to the imbalance of input and output power, during the transient the kinetic energy of the generator increases according to the relation

$$E_k=\frac{1}{2}M\omega^2 \tag{3}$$

where: E_k – kinetic energy of the system after failure [MW.s],
M – moment of inertia of the generator [kg.m^2], ω – angular speed of the generator [rad.s^{-1}].

The maximum duration of short-circuit time, i.e., the maximum possible rate of extension of the clearing time, is limited by the transient stability of the generators and the thermal effects of the short-circuit current. We will get to the practical use of the extension of the line shutdown time later, where we use it to compensate for slight deviations in setting the smart ACR parameters.

B. Length of the dead time

The dead time represents the time interval between the off and on switches of the tripped line. In the case of a temporary failure (for example, a fallen branch on a line, lightning strike, etc.) during a dead time, the normal state is restored, and the normal operating state is restored after ACR. As already mentioned, the length of the dead time is limited by the deionization of the surrounding space and the limit of transient stability. However, the exact length of the dead time for a specific case is not determined and is determined only by the voltage level. The influence of the dead time length on the rotor angle d is shown in Fig. 5. By comparing the waveforms (blue for dead time t = 0.5 s; purple for t = 0.8 s) it is clear that different dead time lengths have different effects on the generator transients at unsuccessful ACR, The effect of the dead time on the amplitude of the rotor angle after an unsuccessful ACR is shown in the last graph of Fig. 5. The graph shows that the dependence is periodic and therefore if due to the short value of the dead time in the first period, it is possible to switch on the line later in the next period (i.e., in our case we are talking not about time t = 0.8 s but about times t = 1.8 s, t = 2.8 s, etc.). In other words, for each transient event, it is possible to set the ACR parameters periodically; in other words, there are several suitable settings of the mentioned ACR parameters for a specific transient event.

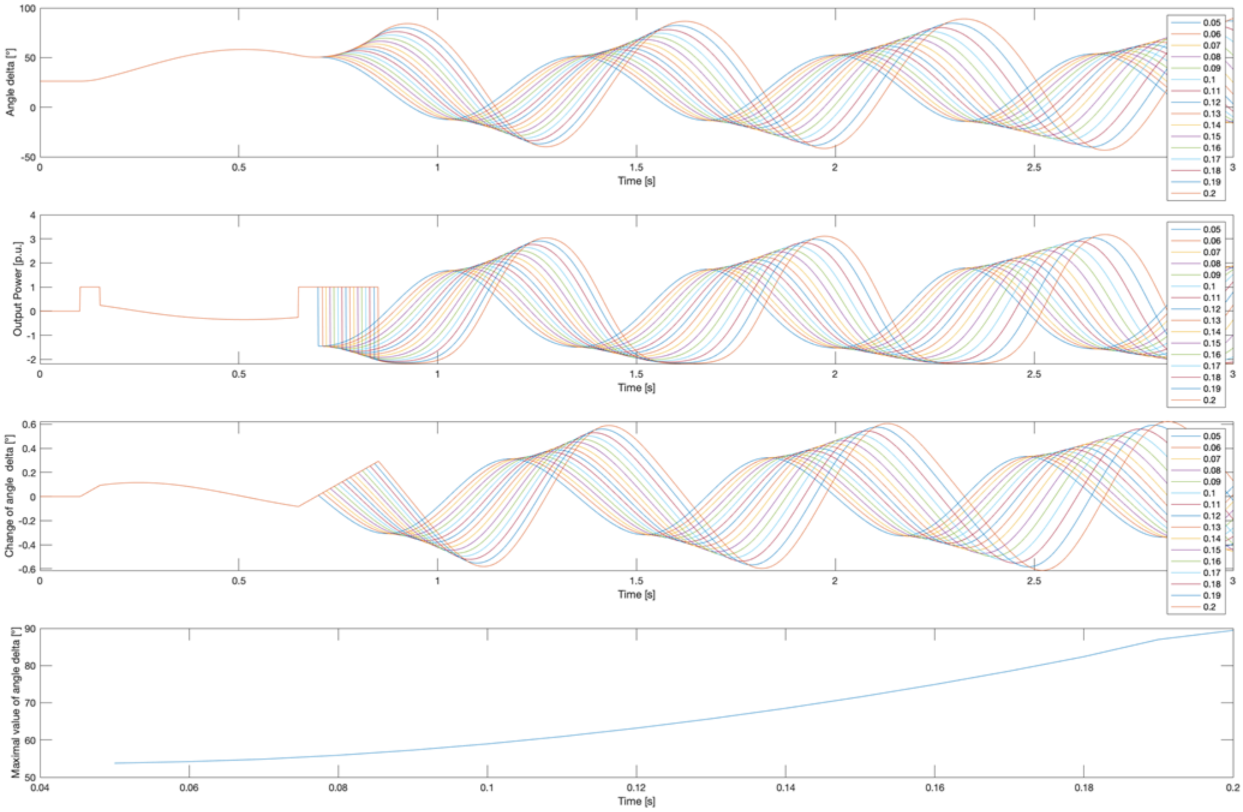


Fig. 4 Impact of second switch-off duration on transient stability

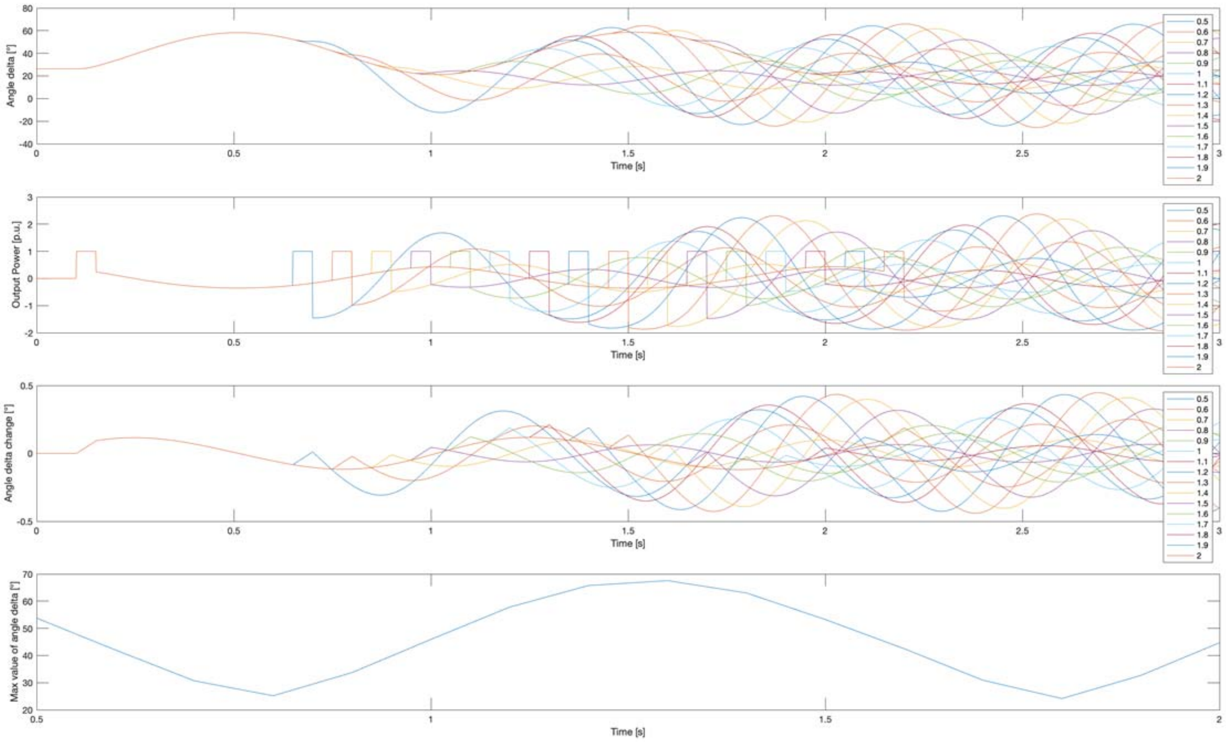


Fig. 5. Effect of length of the dead time on the generator transients

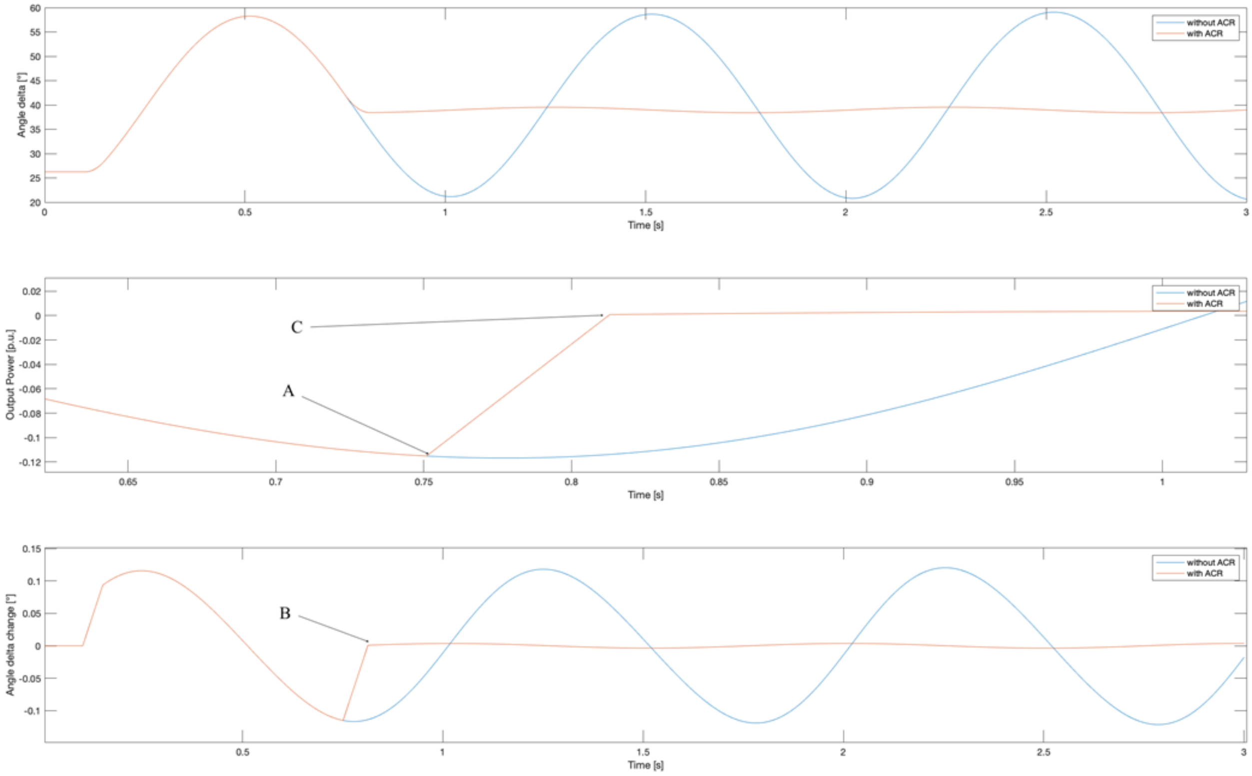


Fig. 6. Impact of correct ACR settings on transient stability

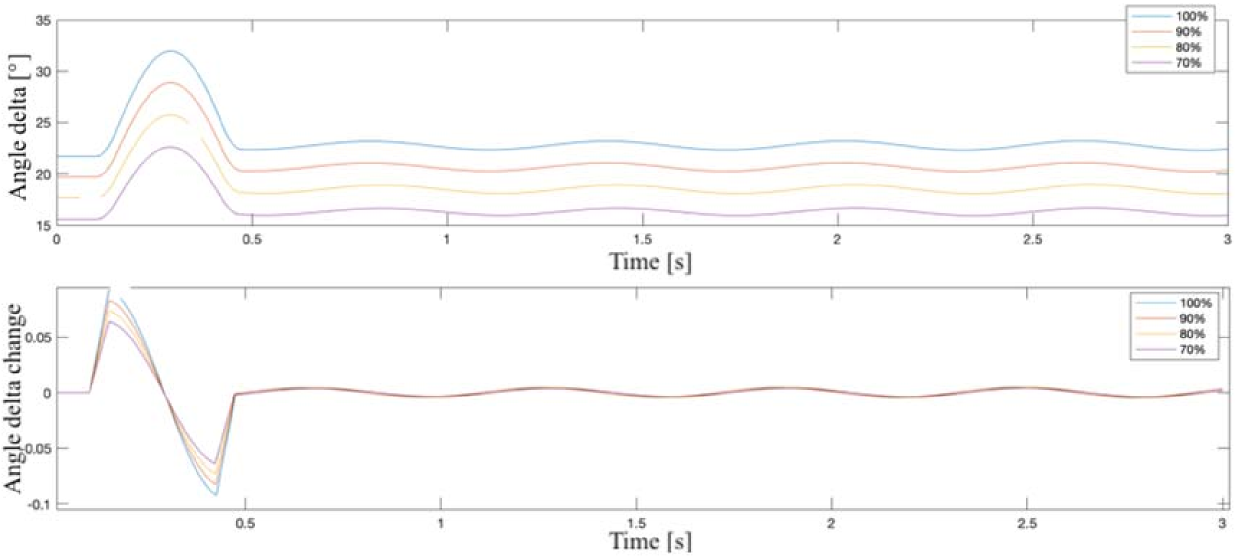


Fig. 7. Impact of the change in active power on transient stability

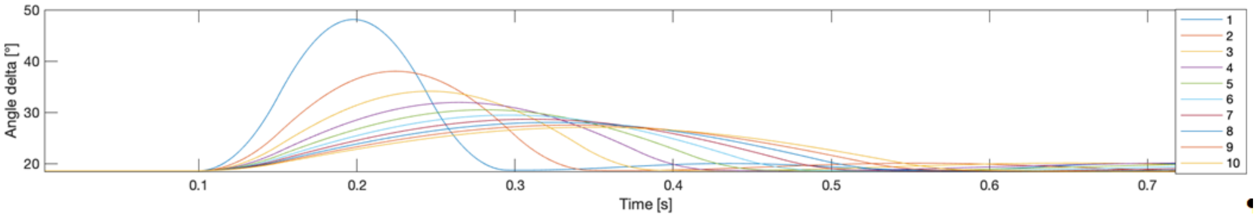
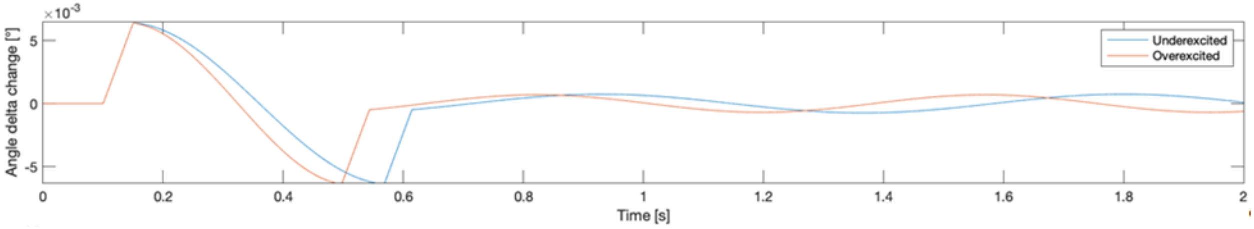


Fig. 8. Influence of H size on the length of the transient period at constant output power of the generator



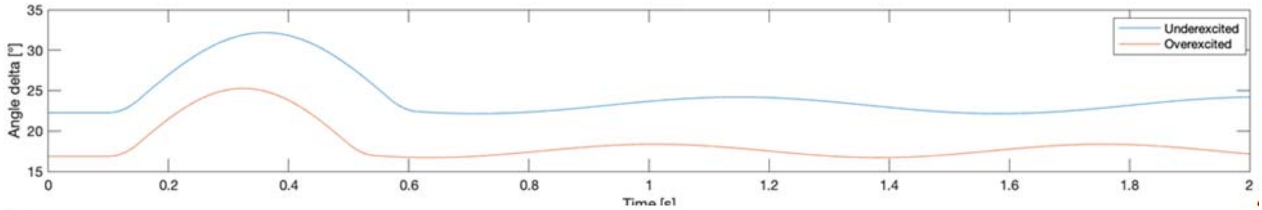


Fig. 9. Influence of generator excitation on the setting of ACR parameters

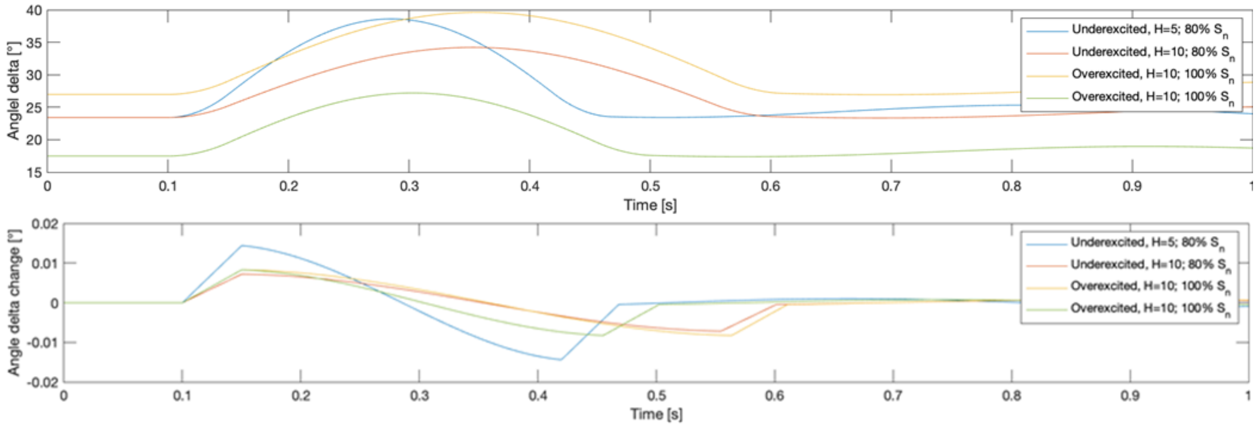


Fig. 10. Influence of generator excitation in connection with the inertia constant H on the setting of ACR parameters

The periodic nature of the course is caused by the different distribution of the generator energy between the potential and the kinetic energy, i.e., at the moment when the kinetic energy of the generator is minimal, its potential energy is maximal and vice versa. It is precisely the ratio of these energies that has a significant effect on the transient process after ACR. However, it should be noted that in the model cases we did not consider the effect of damping, and thus the transient event does not disappear over time but has a periodic constant character. If we also considered the effect of damping, the transient event would gradually disappear over time, and thus the changes in parameters (rotor angle, power, etc.) would gradually mitigate. For this reason, it is desirable (especially in the case of unsuccessful ACR) to switch-on the lines in the first period of the transient, when the amplitudes are maximum.

C. Circuit breaker switch-on speed

The speed of switching on the line, such as the speed of its switching off, is given by the technical parameters of the circuit breakers and the speed of impulse transmission. The effect of the switch-on length does not need to be examined separately, but this parameter must be taken into account when setting the dead time value.

D. Number of failed cycles

For short lines, only one failed ACR cycle is used, mostly due to its impact on the transient stability of the system. In the case of long transmission lines that supply a deficient power zone, multiple ACR cycles are sometimes used, when it is necessary to resume operation as soon as possible. [3]

The right combination of ACR cycle parameters

With the right combination of the length of the dead time and the time delay of the second line switch-off (after a failed ACR), it is possible to minimize the adverse effect of the fault on the power swings in the network. The ideal combination of these parameters is shown in Fig. 6. These parameters were determined based on the energy analysis of the system (generator-infinite bus) before and during the transient [18]

$$E_t = E_k + E_p = \frac{1}{2}M\omega^2 - P_m(\delta - \delta_s) - P_e(cos(\delta) - cos\,\delta_s) \tag{4}$$

where: E_t – transient energy of the system after failure, E_k – kinetic energy of the system after failure, E_p – potential energy of the system after failure, M – moment of inertia of the generator, δ – value of rotor angle after failure, δ_s – equilibrium value of rotor angle after failure.

As the law of conservation of energy applies, the energy Et is equal to the sum of the kinetic and potential energy of the system, and this energy remains constant throughout the transient, we can define the kinetic energy of the system before switching-on the line again as

$$E_k = E_t + P_m(\delta_{ACR} - \delta_s) + P_e(cos\delta_{ACR} - cos\,\delta_s) \tag{5}$$

where the lower index “ACR” indicates the values at the moment before automatic reclosing of the line.

When the line is switched on again, the system energy changes to

$$E_{ACR} = E_k - P_m(\delta_{ACR} - \delta_{sACR}) - P_{eACR}(cos\,\delta_{ARC} - cos\delta_{sACR}) \tag{6}$$

where P_{eACR} is the electrical power supplied to the network after automatic reclosing and δ_{sACR} is the equilibrium point after reclosure.

By combining the relationships of the kinetic energy of the system before reclosure and the total energy E_{ACR} after reclosure, we get the following

$$E_{ACR} = E_t - P_m(\delta_s - \delta_{sACR}) - P_e cos\delta_s + P_{eARC} cos\delta_{sACR} - (P_{eARC} - P_e)cos\delta_{ACR} \tag{7}$$

where all inputs except the angle δ_{ACR} are constants. Since the intensity of the network oscillation is directly proportional to the magnitude of the transient energy E_{ACR}, it is possible to define the moment of minimum oscillations in the system as a relation

$$(8) \qquad min(E_{ACR}) \rightarrow max((P_{eACR} - P_e)cos\delta_{ACR})$$

The sign of the difference $(P_{eACR} - P_e)$ depends on the type of fault, respectively on success of the reclose cycle, in case of transient failure, this difference is positive, on the contrary, in the case of permanent failure (the unsuccessful reclose cycle), this difference is negative. Therefore, the type of fault plays an equally important role in setting the parameters of the ACR cycle. The algorithms used to distinguish between temporary and permanent faults are described, for example, in [19] and [20]. We can write the above relationship for both states as:

Transient fault:

$$min(E_{ACR}) \rightarrow max\big((P_{eACR} - P_e)cos\delta_{ACR}\big) \rightarrow min(\delta_{ACR})$$

Permanent fault:

$$min(E_{ACR}) \rightarrow max\big((P_{eACR} - P_e)cos\delta_{ACR}\big) \rightarrow \\ \rightarrow min(cos\delta_{ACR}) \rightarrow \delta_{ACR} \cong \delta_s$$

If we now look at Fig. 6 (comparison of transients in the event of a failed reclosure and a transient event without the use of ACR), we can state the following for the individual parameters of the ACR cycle:

- Point A - Dead time setting

The length of the dead time must be selected in such a way that the switch-on occurs at the moment when the integral of the difference between the supplied mechanical power and the output electrical power is close to 0 from the positive side:

$$(9) \qquad \int_{t_{off}}^{t_{on}} (P_m - P_e)dt = 0^+$$

At this point, the rotor speed is practically maximum (point A in Fig. 6) but the rotor acceleration is practically zero (point B in Fig. 6). Thus, the kinetic energy of the rotor is maximum. If the generator switches into a short-circuit at this moment, the short-circuit energy will be added to the kinetic energy of the generator, the magnitude of which will be practically identical to the kinetic energy of the rotor (the damping effect on the rotor is neglected) just with the opposite sign. If we switch off the damaged line at the correct moment (point C in Fig. 6), i.e., at the moment when the angular velocity is equal to 0, we get practically no power swing after switching off the line.

- Point B - Line shutdown speed

Delayed line shutdown for a few milliseconds helps compensate the slight energy differences. The ideal switch-off moment can be defined as

$$(10) \qquad \frac{d\delta}{dt} = 0$$

i.e., the line must be switched on when the angle change is zero. The given moment can be seen in Fig. 6.

The length of the dead time and the switch-off moment were selected according to the principles mentioned above. After the reclosure, even though it was unsuccessful, it can be seen that the transient event has practically disappeared - the value of the angle after the failed reclosure is practically stable.

Influence of output power of the generator on stability

The active and reactive output power of the generator has a significant effect on its transient stability. The higher active power of the generator, the more the operating point of the curve P = f (δ) moves to its maximum and thus also reduces the braking area at the expense of accelerating area. Simply put, the critical clearing time is shorter and value of critical angle δ_{crit} is smaller. The equation below describes the impact of the output active power of the generator on these quantities.

$$(11) \qquad P_e = \frac{EU}{X}\sin\delta = \frac{U}{X}Abs\big(\bar{U}_g + jX'_d\bar{I}_g\big) = \\ \frac{U}{X}Abs\left(\bar{U}_g + jX'_d\left(\frac{\bar{S}_g}{\bar{U}_g}\right)^*\right)$$

$$(12) \qquad \delta_{crit} = cos^{-1}\left(\frac{P_e(\pi-2\delta_0)+P^I_{max}cos(\pi-\delta_0)}{P^I_{max}}\right)$$

where: I_g – current of the generator, S_g – apparent power of the generator, X'_d – transient reactance of the generator.

As for the impact on the ACR cycle, or more precisely its setting, the generator load has a practically negligible effect on the length of the swing period (Fig. 7), the load change causes only minimal deviations in its size, while the inertia constant does not play a significant role in setting dead time length. In the case of lightweight generators, the swing period is of the order of several milliseconds for H = 1, but if we take into account the time required to deionize the surrounding space, the effect of the load on the length of the dead time will be only about 5% at 50% change in output power.

However, regarding lightweight generators, more emphasis needs to be placed on the accuracy and correct timing of circuit breakers, as the transient period is relatively small (the effect of size H on the transient period length at constant load is shown in Fig. 8). The results of simulations of excitation and generator load are shown in Fig. 9. It can be seen from the figures that the change in active power was practically not reflected in the parameters of the ACR cycle (as in our case a heavy generator was used), which does not apply to the change power - the length of the dead time has been considerably extended here.

The individual influences of the parameters on the setting of the ACR are obvious from the courses, in short, we could summarize them as follows:

- The inertia constant significantly affects the amplitude of the angle during the transient and thus also the length of dead time; this is due to the fact that the lighter machine achieves a higher angular velocity and acceleration during failure.
- The output active power of the generator has only a slight effect on the parameter settings. However, in the case of lightweight generators, precise switching timing is required.
- The excitation of the generator significantly affects the length of the dead time, as it has a significant effect on the length of the transient period.

Design of smart ACR

As the situation within the power system is constantly changing, in order to select the ideal parameters of the ACR cycle, it is necessary to determine them in real time according to the current situation in the network. As already mentioned, as the given process presupposes the prolongation of the short-circuit effect on the power system, it is necessary to monitor their condition, i.e., heat reserve so that in the event that the limit value could be exceeded, the line is switched-off immediately.

Therefore, the smart ACR requires real-time monitoring of the state of the power system. In order to determine the length of the dead time, it is necessary to monitor the power oscillations, ideally on the line from the power plant or integration block monitoring power oscillations, as described in the previous chapter. With respect to the switching moment, it is necessary to monitor the change in the delta angle. The block diagram of the smart ACR is shown in Fig. 11.

The timer in the smart ACR scheme ensures that the line is not switched on sooner so that the surrounding space is deionized.

Subsequently, with the help of the integrating power block, the dead time will be determined according to the principles described in the previous chapters.

Subsequently, 3 blocks are needed to determine the switching moment: a derivative block monitoring the angle value d, an integrating block monitoring the line current value, and an IoT device monitoring the current heating of the device and its comparison with the allowed heating values.

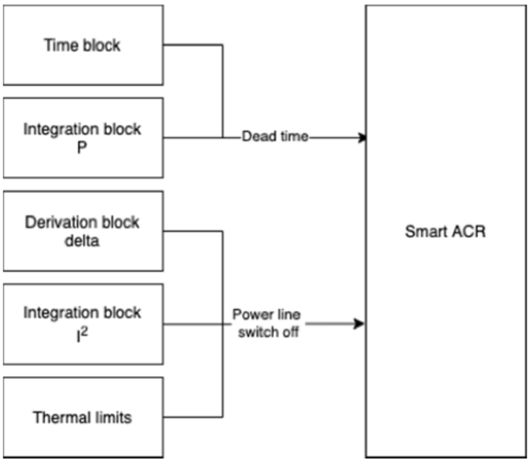


Fig. 11. Block diagram of smart ACR

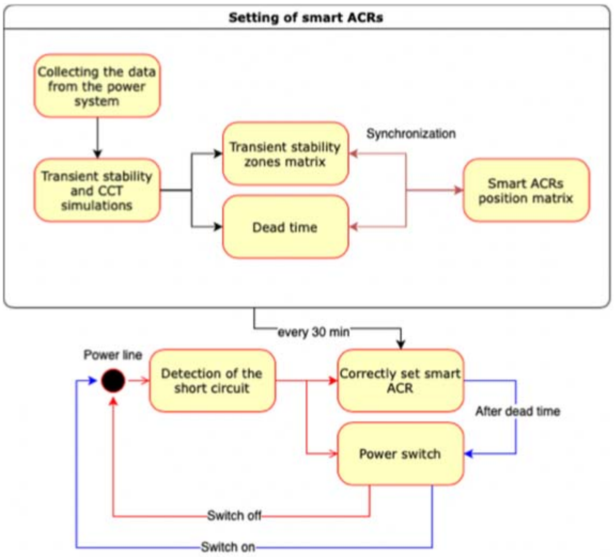


Fig. 12. Smart ACR concept concerning [4]

Returning to the example in Fig. 6, we can say that the derivative term evaluated the moment of line shutdown at time t = 0.75s, which represents a short-circuit duration of 0.053 s. As the short-circuit duration is relatively small (e.g., compared to the short-circuit duration in case of circuit breaker failure, the short-circuit duration is greater and equal to the time delay of the second distance protection zone), it is not necessary to calculate warming of power system equipment (lines, transformers, etc.). If a longer short-circuit duration would be required (e.g., in the case of heavyweight generators with a large swing period), it would be necessary to calculate, resp. also to check the values of short-circuit current and warming of individual devices.

Another variant of the smart ACR application is given in [4]. The publication talks about the central setting of ACR cycles, while the individual times are calculated centrally on the basis of data collected from phasor measurements in the system. The diagram of this smart ACR concept is shown in Fig. 12.

The calculation algorithm can be mathematically described as follows:

1) From the collected data, the values of the critical rotor angle and critical clearing time (CCT) are calculated according to the following

$$\delta_{crit} = cos^{-1}\left(\frac{P_e(\pi - 2\delta_0) + P_{max}^I cos(\pi - \delta_0)}{P_{max}^I}\right)$$

$$CCT = \sqrt{\frac{4HS_{rG}}{\omega_0 P_e}(\delta_{crit} - \delta_0)}$$

2) A matrix of transient stability lost zones is compiled according to the calculated CCT values

$$DSLZ = \begin{bmatrix} CCT_1^1 & ... & CCT_j^1 \\ ... & ... & ... \\ CCT_1^i & .... & CCT_j^i \end{bmatrix}$$

$$CCT_j^i = \begin{cases} ak\left(CCT_j^i\right) = max\left(CCT_j\right); CCT_j^i \\ 0 \end{cases}$$

where: j represents the j-th generator in the network, i represents the i- th line in the network on which the short-circuit occurred

3) Calculation of ACR cycle parameters for a given zone – length of the dead time

$$\int_{t_{off}}^{t_{on}} (P_m - P_e)dt = 0^+$$

4) Calculation of ACR cycle parameters for a given zone – speed of the line switch-on

$$\frac{d\delta}{dt} = 0$$

Conclusion

With the gradual digitization and the advent of fast 5G networks, new possibilities are opening up for protection and automation of individual processes, not only in the electrical power engineering. Smart devices are gradually replacing traditional systems and helping operators respond more flexibly and quickly to changes in the power system. However, these devices often require real-time data collection from the system with sufficient accuracy; not only of the rms values but also of individual partial data, while traditional instrument transformers do not always meet these requirements; this problem can be solved by replacing traditional instrument transformers with unconventional sensors. After solving real-time data collection problems, there is also room to use the smart ACR concept designed in this paper. In compiling the concept, we based on the analysis of the effects of individual parameters on the transients after the failure, specifically we analyzed the effects of active and reactive output power of the generator, inertia constant, and individual times in the ACR cycle. For the correct of the ACR settings, it is necessary to know the nature of the fault and more precisely whether it is a temporary or permanent fault, as it is necessary to correctly set the moment of reclosing of the line based on the type of fault. In the case of a transient fault, it is the moment when the rotor angle is minimal, and conversely, in the case of a permanent fault, it is necessary to switch-on the line when the rotor angle value is the same as value before the fault.

Analyzing the results, we found that during the setting of ACR it is necessary not only to set the correct length of the dead time but also in case of unsuccessful reclosure the duration of short-circuit. With correct settings of ACR we could minimize power oscillations in the system after an unsuccessful cycle. Here, it is necessary to realize which parameters significantly affect the length of the dead time - one of the parameters examined is the excitation of the generator, which significantly affects the length of the transient period and thus ultimately the length of the dead time, the inertia constant, but it is necessary to take it into account from the point of view of system development as such, as lightweight generators have shorter periods during transients, but on the contrary, the amplitudes of changes are significantly higher. The effect of the active output power of the generator is not so significant (in the interval from about 70% of nominal power), but it can also play an important role in the case of lightweight generators, where it is necessary to emphasize the accuracy of the timing of switching processes.

In comparison with the already introduced concepts of adaptive setting of the dead time, our concept of smart ACR considers its use not only in the case of transient faults, but also in the case of permanent faults, with the difference that depending on the type of fault, the length of the dead time in order to dampen oscillations in the power system.

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