Internal Winding Fault Protection for Shunt Reactors

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Abstract **– Existing protection techniques for shunt reactors can't guarantee sufficient sensitivity for inter-winding faults due to limited precision of current transformer. To solve this usage problem of input resistance of resonance contour formed by reactor bank inductance attaching wiring capacitance is proposed. Difference between input resistance profiles of damaged and healthy bank is used as a fault criterion.**

Keywords **– shunt reactors protection, impedance profile.**

I. Introduction

Oversupply of reactive power generated by power lines leads to overvoltage and preliminary aging of equipment. Moreover, capacitive loading of generators may lead to self-excitation and endanger system stability. Installation of shunting reactors (ShR) helps to keep reactive power under control. Different kinds of protection are used for ShR. The most popular of them are over current protection, distance protection (mostly using reserved zones of line terminals) and differential protections. For protection of split-faze reactors unbalance relays can be incorporated. Usage of reverse sequence over current relays can give good results, especially for mono-coil reactors, where such relays are the most sensitive for inter-winding faults. But all mentioned protection techniques do not guarantee safe protection against inter-winding faults, especially when only a small part of the whole winding is short-circled. The common source of low sensitivity lays in the current transformer (CT) error. The change in the current caused by fault may be much smaller than CT error. Usage of resonance characteristics is proposed to solve inter-winding fault protection problem.

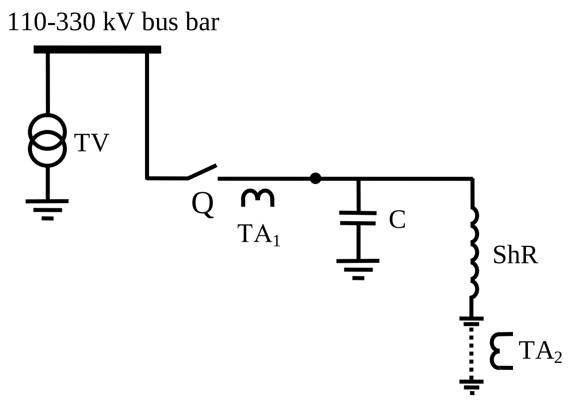

Fig. 1. ShR connection to the 110-330 kV bus bar

II. Shunt Reactor as a Resonance Contour

Let's discuss connection scheme for one bank of ShR at 110 – 330 kV substation (Fig. 1).

The ShR phase bank is connected to the bus bar through the circuit breaker *Q*; attachment current is controlled using current transformer TA_1; control over earth current for differential protection is maintained using TA_2. Voltage transformer *TV* is used to measure bus voltage. Capacitor "*C*" represents connection wires to earth capacity plus bank high voltage input terminal capacity. Relatively to the "a" point ShR with connection bus may be represented as *RLC* circuit as shown in Fig. 2 (ignoring connection bus resistance)

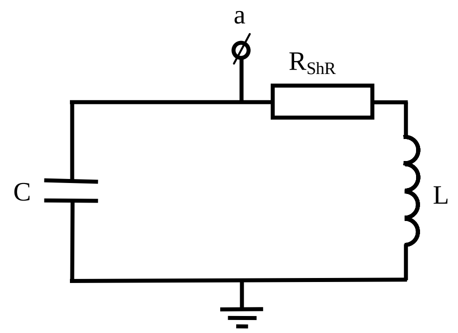

Fig. 2. Equivalent scheme of ShR with connected bus

where *C* is capacity to the earth of ShR input terminal and of connection bus; *L* is ShR inductance; and R_{ShR} is winding resistance. If the whole winding consists of *m* turns, the whole active resistance will be $R_{ShR}=\sum_{i=1}^{m} R_i$, where R_i is active resistance of wind number *i*. Relatively "a" point circuit may be considered as an oscillating contour where current resonance is possible. Resonance frequency is determined from the equation:

$$J_m(Y_{in})=0 \tag{1}$$

or

$$J_m\left(j\omega C+\frac{1}{j\omega L+R_{ShR}}\right)=0. \tag{2}$$

Transformation of equation (2) leads to:

$$J_m\left(j\omega C+\frac{R_{ShR}-j\omega L}{+R_{ShR}^2+\omega^2L^2}\right)=0,$$

or $\omega^2CL^2+R_{ShR}^2C-L=0.$

Relative frequency ω_r (resonance frequency) is determined in the following way:

$$\omega_r=\frac{1}{\sqrt{LC}}\cdot\sqrt{1-\frac{R_{ShR}^2C}{L}}. \tag{3}$$

Input conductance at the resonance frequency is purely active and is equal to:

$$G_{in}=\frac{R_{ShR}^2}{R_{ShR}^2+\omega_r^2L^2}, \tag{4}$$

$$R_{in} = R_{ShR} + \frac{\omega_r^2 L^2}{R_{ShR}}. \tag{5}$$

III. Fault Regime of Shunting Reactors

Let's now discuss ShR where *n* from total *m* winding turns are short-circuited. The simplified scheme is shown in Fig. 3.

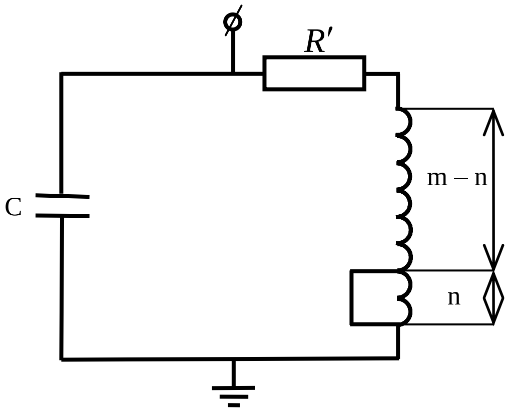

Fig. 3. ShR when *n* turns of winding are short – circuited

Such ShR may be considered as transformer with one winding of *m-n* turns and another one with *n* turns (Fig. 4).

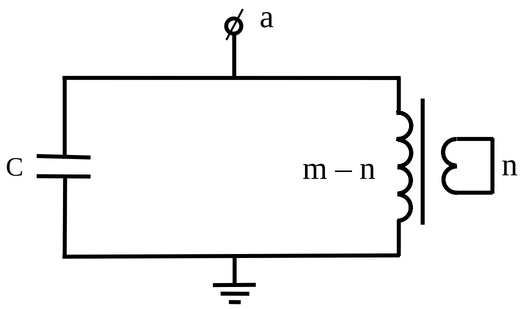

Fig. 4. Faulty ShR as transformer

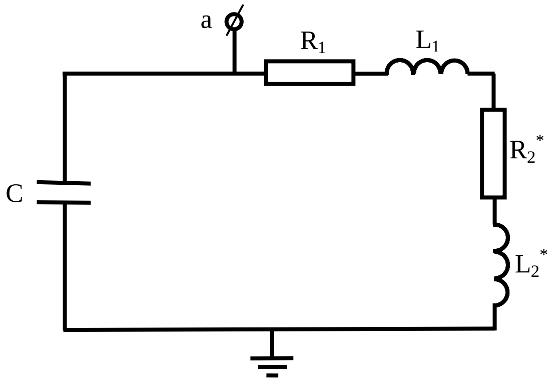

Fig. 5. Equivalent scheme

In Fig. 5 the contour equivalent scheme is shown. Resistance R_2^* and inductance L_2^* are reduced to the primary winding, particularly $R_2^* = \sum_{i=1}^{n} r_i \cdot \left(\frac{m-n}{n}\right)^2$ and input resistance at the resonance frequency is:

$$R'_{in} = \sum_{i=1}^{n} r_i \cdot \left(\frac{m-n}{n}\right)^2 + \sum_{j=n}^{m} r_j + \frac{(\omega \cdot L')^2}{\sum_{i=1}^{n} r_i \cdot \left(\frac{m-n}{n}\right)^2 + \sum_{j=n}^{m} r_j}. \tag{6}$$

For healthy ShR:

$$R_{in} = \sum_{i=1}^{n} r_i + \sum_{j=n}^{m} r_j + \frac{(\omega \cdot L)^2}{\sum_{i=1}^{n} r_i + \sum_{j=n}^{m} r_j}. \tag{7}$$

Denoting $\sum_{i=1}^{n} r_i$ as r_a and $\sum_{j=n}^{m} r_j = r_b$ equations (6) and (7) may be rewritten as (8) and (9)

$$R'_{in} = r_a \cdot \left(\frac{m-n}{n}\right)^2 + r_b + \frac{(\omega \cdot L')^2}{r_a \cdot \left(\frac{m-n}{n}\right)^2 + r_b}, \tag{8}$$

$$R'_{in} = r_a + r_b + \frac{(\omega \cdot L)^2}{r_a + r_b}. \tag{9}$$

It is obvious that in case of faulty ShR, failed winding part appears in the contour input resistance as value $\left(\frac{m-n}{n}\right)^2 - 1$ times bigger than that in case of healthy ShR. Resonance frequency will be changed because inductance L' includes failed winding part with ratio $\left(\frac{m-n}{n}\right)^2$. Input resistance chart depending on frequency with different *n* as it is shown in Fig. 6.

IV. Protective Device Description

Thus, short-circuit in the ShR winding may be discovered by change of resonance contour input resistance. To measure such resistance at different frequencies presence of high harmonics in the network voltage may be used. Using Fourier transformation a spectrum of bus voltage $U(\omega)$ and ShR current $I(\omega)$ may be acquired and the so-called "frequency profile" of contour input resistance $Z(\omega)$ can be derived branches, profiles. Such measure will also reduce the impact of CT errors. Possible device architecture is shown in Fig. 7.

Input voltages and currents are filtered by analogue filters to reject components with frequencies above Nyquist frequency, converted to digital form by a set of Analog-to-Digital converters; and spectrum analysis is performed with Fast Fourier Transformation routine. Resistance profile increase in real part of $Z(\omega)$ at frequencies close to resonance $\omega_r = \frac{1}{\sqrt{LC}}$ is a clear signal of inter winding fault. A memory stored profile may be used as a reference profile, but

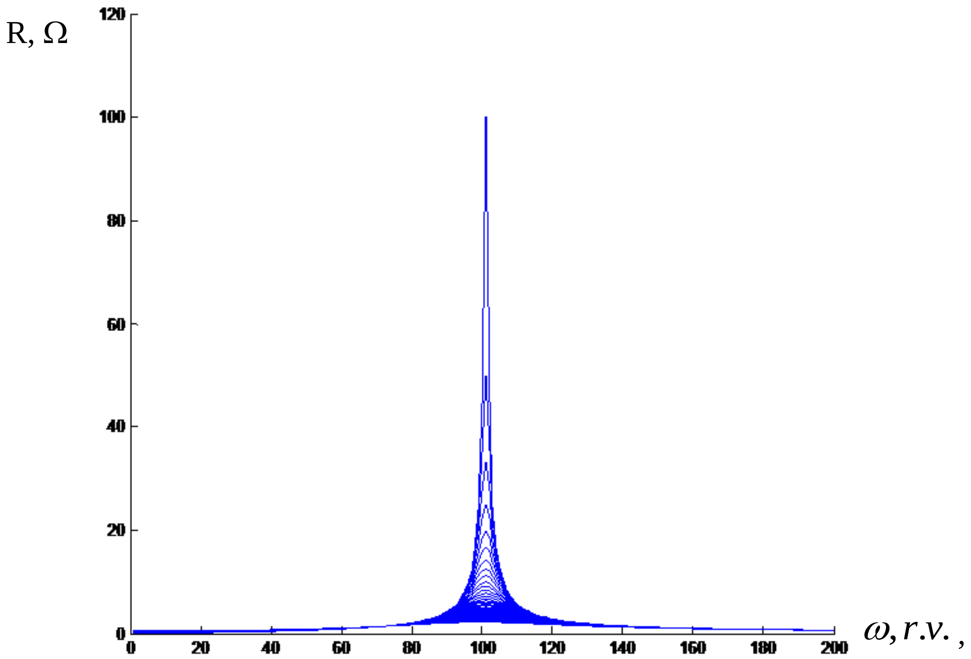

Fig. 6. Input resistance as function of frequency

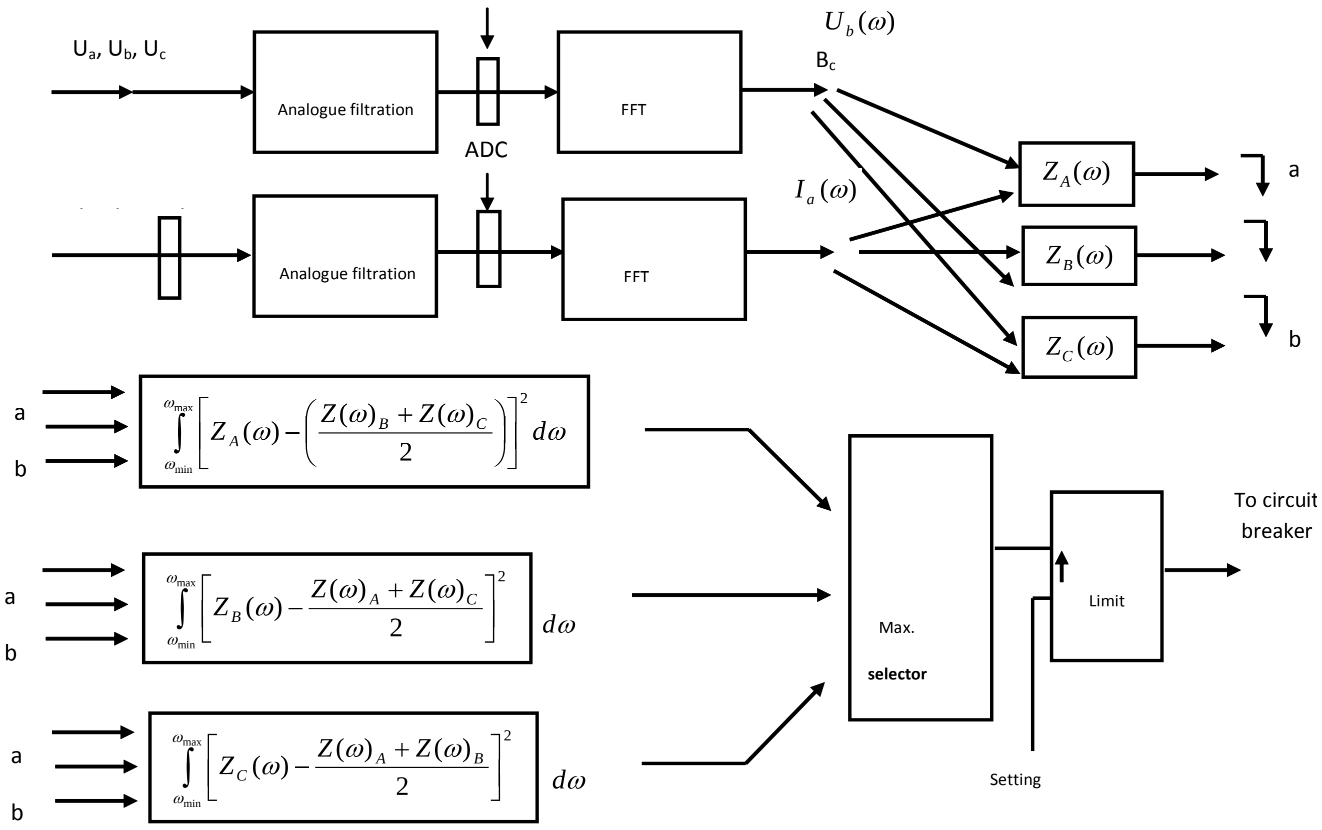

Fig. 7. Device architecture

changes in winding resistance caused by temperature change will make the usage of quite significant dead zone unavoidable and will lead to decrease in protection sensitivity. More preferable solution is to use another bank profile as a reference average of other banks or, in case of split – winding reactor parallel $\dot{Z}(\omega)$ or to simplify calculations it is a real part $R_{in}(\omega)$ is calculated on the basis of Fourier coefficients. Integral equation (10) may be used as profile-to-profile difference criteria.

$$\Delta_A = \int_{\omega_{\min}}^{\omega_{\max}} \left[Z_A(\omega) - \frac{(Z_B(\omega) + Z_C(\omega))}{2} \right]^2 d\omega. \qquad (10)$$

Physically it represents energy of difference between A phase profile and average of B and C, dissipated on 1 ohm resistor. Minimal frequency ω_{min} should be below resonance ω_r. ω_{max} should never be higher than Nyquist frequency. Using real part of input resistance the only differences will be:

$$\Delta_A = \int_{\omega_{\min}}^{\omega_{\max}} \left[R_a(\omega) - \frac{R_B(\omega) + R_C(\omega)}{2} \right]^2 d\omega,$$

$$\Delta_B = \int_{\omega_{\min}}^{\omega_{\max}} \left[R_b(\omega) - \frac{R_A(\omega) + R_C(\omega)}{2} \right]^2 d\omega, \qquad (11)$$

$$\Delta_C = \int_{\omega_{\min}}^{\omega_{\max}} \left[R_c(\omega) - \frac{R_A(\omega) + R_B(\omega)}{2} \right]^2 d\omega.$$

Digital integration techniques may be used to calculate equations (11). In case of ideal device Fourier transformation will yield a bar function which has non-zero values only at frequencies which are multiplied by main frequency. In case of real device, profile will have non-zero values for all frequencies due to limited precision of clock oscillator. But since all the values are measured in the united time base, all errors will have uniform structure and (11) may be replaced by sum, for example, Δ_A when $\omega_{\min} = \omega_0$ is

$$\Delta_A = \sum_{U=1}^{K_n} \left[R_a(K\omega_0) - \frac{R_B(K\omega_0) + R_C(K\omega_0)}{2} \right]^2 \cdot \frac{(\omega_{\max} - \omega_0)}{K_n}, \quad (12)$$

where ω_0 is fundamental harmonics frequency, for 50 Hz networks $\omega_0 = 100\pi$, $K_n = \mathrm{int}\left(\frac{\omega_{\max}}{\omega_o}\right)$. To reduce real-time calculus, volume multiplier $\frac{\omega_{\max} - \omega_0}{K_n}$ may be included within settings.

A command to break the circle is given if value $\max \begin{bmatrix} \Delta_A \\ \Delta_B \\ \Delta_C \end{bmatrix}$ becomes bigger than square of setting value.

V. Conclusion

Usage of ShR input resistance change at resonance frequency allows creating a highly sensitive protection against inter-winding faults.

VII. References

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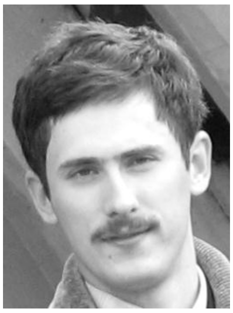

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Aleksandrs Dolgicers, Dmitrijs Antonovs. Šuntējošo reaktoru aizsardzība no starpvijumu īsslēgumiem.
Reaktīvas jaudas pārpalikums, kas tiek ģenerēts līnijās, noved līdz sprieguma līmeņa paaugstinājumam, kas, savukārt, izraisa ierīces priekšlaicīgu iziešanu no darba un apdraud energosistēmas stabilitāti. Lai kompensētu reaktīvas jaudas pārpalikumu tiek lietoti šuntējošie reaktori. Lai aizsargātu šuntējošus reaktorus no bojājumiem tiek lietotas maksimālās strāvas aizsardzības, distantaizsardzības rezerves zonas un diferenciālā aizsardzība. Tomēr, augstākminētās aizsardzības nenodrošina precīzu strapvijumu īsslēgumu noteikšanu. Zema aizsardzības jutīguma iemesls ir strāvas izmaiņas, kuras izraisa īsslēgumu, samērojums ar strāvmaiņu mērīšanas precizitāti. Lai risinātu starpvijumu īsslēgumu problēmu, tiek piedāvāts lietot ieejas kontūra pretestības izmaiņas frekvencēs tuvas kontūra rezonanses frekvencei.
Lai noteiktu bojājumus, tiek piedāvāts salīdzināt aktīvās pretestības profilu, kas atkarīgs no frekvences, ar vidējo divu paliekošo fāžu reaktoriem ar nešķeltiem tinumiem un paralēla zara profilu reaktoriem ar šķeltiem tinumiem. Pielietojot ieejas pretestības izmaiņas šuntējošiem reaktoriem frekvenču diapazonā, kas ir tuvs rezonanses frekvencei, dod iespēju izveidot augsti jūtīgu aizsardzību pret starpvijumu bojājumiem.

Александр Долгицер, Дмитрий Антонов. Защита шунтирующих реакторов от межвитковых замыканий.
Избыток реактивной мощности, генерируемой линиями, ведет к повышению уровня напряжения, что, в свою очередь, приведет к преждевременному выходу оборудования из строя и угрожает устойчивости энергосистемы. Для компенсации избыточной реактивной мощности используются шунтирующие реакторы. Для защиты шунтирующих реакторов от повреждений используют максимальные токовые защиты, резервные зоны дистанционных защит и дифференциальные защиты. Однако перечисленные защиты не обеспечивают надежного обнаружения межвитковых замыканий. Причиной низкой чувствительности защит является соизмеримость изменения тока, вызванного замыканием, с погрешностью трансформатора тока. Для решения проблемы межвитковых замыканий предлагается использовать изменение входного сопротивления контура при частотах близких к резонансной частоте контура.
Повреждения определяются сравнением профиля зависимости активного сопротивления от частоты со средним значением двух других фаз для реакторов с нерасщеплёнными обмотками и профилем параллельной ветви для реакторов с расщеплёнными обмотками. Использование изменения входного сопротивления шунтирующих реакторов в диапазоне частот близких к резонансной частоте, позволяет создать высокочувствительную защиту против межвитковых повреждений.