Chapter 5

PHASE-DOMAIN SYNCHRONOUS MACHINE

5.1 INTRODUCTION

This synchronous machine can represents round or salient pole machines operating as motors or generators without using Park's transformation. Exploiting the winding functions theory, the effect of non-sinusoidal windings are included in the simulation. Furthermore, several different stator internal faults can be simulated and their impact on multiple parallel windings can be observed. The neutral impedance is user-specified.

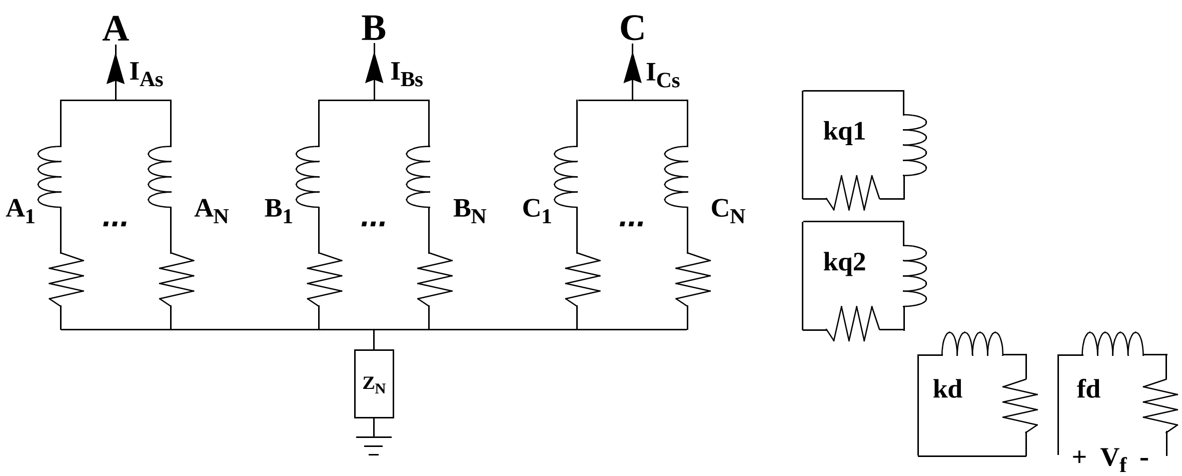

Figure 5 - 1 Multiple parallel windings synchronous machine with neutral impedance (round rotor)

This block includes the electrical model and a 1-mass mechanical model. Other systems such as turbine, excitation system, stabilizer, etc. are not integrated in this model and have to be externally implemented.

Implemented stator internal faults are

1- Single winding to ground

2- Phase-phase shorted windings

3- Phase-phase windings to ground

4- Three phase shorted windings

5- Three phase windings to ground

6- Single phase shorted windings

7- Single phase windings to ground

8- Single winding shorted turns

5.2 Model Overview

The stator is composed of N parallel windings per phase, all connected to ground with a Z_N impedance. The N parallel windings of one phase are spatially distributed around the stator. Their positions is used to compute the winding functions necessary for the self and mutual inductance parameters.

The rotoric circuit is composed of the field winding and one damper winding in the direct axis while the quadrature axis contains one or two damper windings for saliant or round rotors respectively. All damper windings are shorted.

The block diagram of the phase-domain machine is shown in Figure 5 - 2.

The stator reactance matrix for a single winding per phase machine is given as

$$X_s = \begin{bmatrix} X_{ls} + X_{Axx} - X_{Bxx}\cos 2\theta & X_{Axy} - X_{Bxy}\cos\left(2\theta - \frac{2\pi}{3}\right) & X_{Axy} - X_{Bxy}\cos\left(2\theta + \frac{2\pi}{3}\right) \\ X_{Axy} - X_{Bxy}\cos\left(2\theta - \frac{2\pi}{3}\right) & X_{ls} + X_{Axx} - X_{Bxx}\cos\left(2\theta + \frac{2\pi}{3}\right) & X_{Axy} - X_{Bxy}\cos 2\theta \\ X_{Axy} - X_{Bxy}\cos\left(2\theta + \frac{2\pi}{3}\right) & X_{Axy} - X_{Bxy}\cos 2\theta & L_{ls} + X_{Axx} - X_{Bxx}\cos\left(2\theta - \frac{2\pi}{3}\right) \end{bmatrix}$$

where X_{ls} is the leakage reactance, X_{Axx} and X_{Bxx} are the constant and time-variant part of the self reactance while X_{Axy} and X_{Bxy} are for the mutual reactances. Finally, θ is the rotor electrical angle. The X_A and X_B parameters are calculated from the winding functions. The mutual reactance matrix between the stator and the rotor, refered to the stator for a salient-pole machine, is

$$X'_{sr} = \begin{bmatrix} X_{mq}\cos\theta & X_{md}\cos\theta & X_{md}\cos\theta \\ X_{mq}\cos\left(\theta - \frac{2\pi}{3}\right) & X_{md}\cos\left(\theta - \frac{2\pi}{3}\right) & X_{md}\cos\left(\theta - \frac{2\pi}{3}\right) \\ X_{mq}\cos\left(\theta + \frac{2\pi}{3}\right) & X_{md}\cos\left(\theta + \frac{2\pi}{3}\right) & X_{md}\cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}$$

where X_{md} and X_{mq} are the magnetizing reactance for the direct and quadrature axis respectively. Finally, the rotor reactance matrix, refered to the stator takes the following form.

$$X'_r = \begin{bmatrix} X_{lkq} + X_{mq} & 0 & 0 \\ 0 & X_{lfd} + X_{md} & X_{md} \\ 0 & X_{md} & X_{lkd} + X_{md} \end{bmatrix}$$

X_{lkq}, X_{lfd} and X_{lkd} are the leakage reactance for the q-axis damper, the field winding and the d-axis damper.

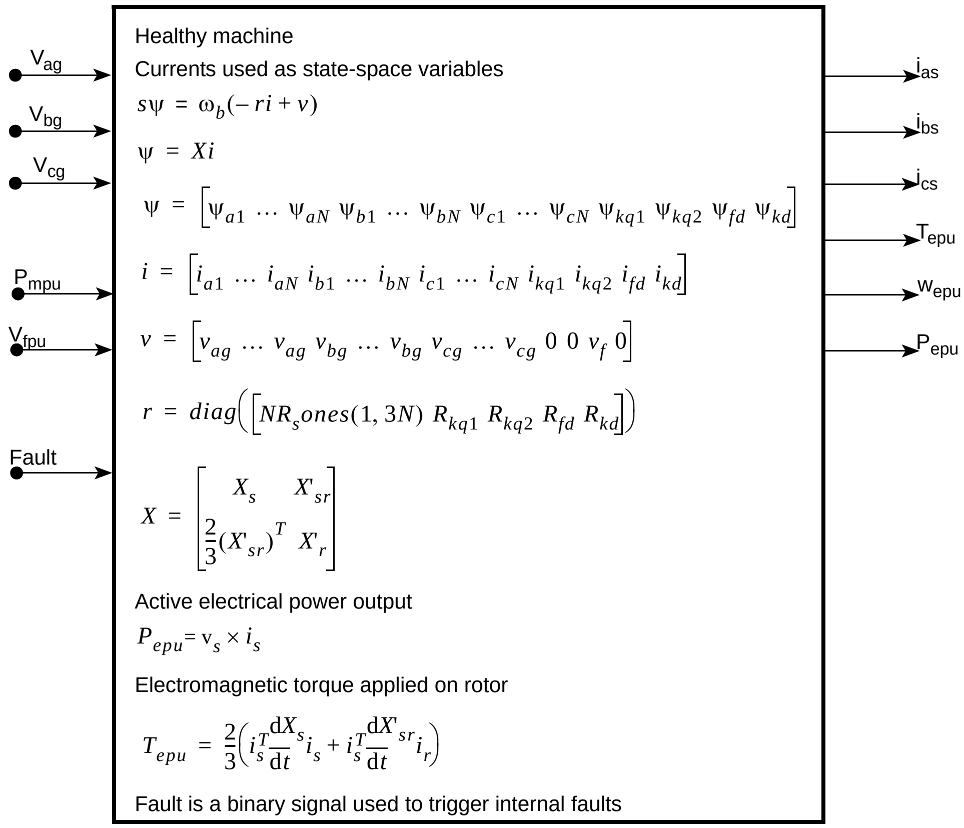

Figure 5 - 2 Phase-Domain Synchronous Machine Block Diagram (healthy machine)

5.2.1 Programmable General Parameters

- S_{base}: Base nominal electrical power of generator (MVA);
- V_{baseLL}: Base nominal voltage (kV);
- w_b: Base nominal angular frequency (elec. rad/s);

5.2.2 Programmable Parameters

The following parameters are required for simulation. The use of the parameter generator is ***mandatory***.

- Xls: Armature leakage reactance (pu);
- Xmd: Direct magnetizing reactance (pu);
- Xmq: Quadrature magnetizing reactance (pu);
- Xlkq1: Quadrature damper winding 1 leakage reactance (stator side) (pu);
- Xlkq2: Quadrature damper winding 2 leakage reactance (stator side) (pu);
- Xlfd: Field winding leakage reactance (stator side) (pu);
- Xlkd: Direct damper winding leakage reactance (stator side) (pu);
- Rs: Armature resistance (pu);

- Rkq1: Quadrature damper winding 1 resistance (stator side) (pu);
- Rkq2: Quadrature damper winding 2 resistance (stator side) (pu);
- Rfd: Field winding resistance (stator side) (pu);
- Rkd: Direct damper winding resistance (stator side) (pu);
- Rg, Xg: Neutral resistance and reactance (pu);
- H: Inertia constant (pu.s);
- F: Friction constant (pu);
- P: Number of poles;
- N_slot: Number of stator slots;
- N_cs: Number of conductors per slot;
- N: Number of parallel windings per phase;
- Winding functions for complete phase and each individual windings.

5.2.3 List of Available Signals

At acquisition, the following signals are made available by the **sensors**:

- Iat, Ibt, Ict: Phase current at the machine's terminals (A);
- Ian, Ibn, Icn: Phase current at the machine's neutral point (A);
- IAx, IBx, ICx: Parallel winding x current (pu);
- IAfx, IBfx, ICfx: Faulted winding current (x odd: top part; x even: bottom part) (pu);
- In: Neutral current (A);
- Idef: Fault current (A);
- Ifd, Ikd, Ikq1, Ikq2: Rotor windings current (pu);
- w: Electric angular speed (pu);
- Te: Electrical torque (pu);
- Pe: Electric active power (pu);
- Theta: Rotor electrical angle (rad).

5.3 WINDING FUNCTIONS

5.3.1 Introduction

Typically, machine models assume that windings' spatial distribution around the stator is sinusoidal. This is very practical since inductance calculations and the overall model are drastically simplified. On the other hand, since this hypothesis neglects spatial harmonics and asymetries in the windings, those models cannot directly take into account phenomena, such as internal faults, that introduce asymetries.

The present model does not make this assumption but additional informations about the stator windings are necessary to establish the winding functions. a simple mathematical tool that enables the treatment of non sinusoidal stator windings.

5.3.2 Necessary Parameters

To establish the winding functions of a particular machine, one needs to know the following parameters and informations:

- The number of poles;
- The number of slot in the stator armature;
- The number of conductors per slot;
- The number of parallel windings per phase;
- The slot sequence for each individual winding.

With those informations, the winding function for each winding and for each whole phase can be calculated.

5.3.3 Method

First of all, all slot sequence numbers have to be shifted to align slot 1 and the middle of a pole winding of phase A. Then, a «positive» direction must be established. Typically, the winding current flows up or down a bar in the stator's slot, so one of those direction is labelled positive. Finally, one goes through all the stator's slots, adding z for each positive bars and substrating the same value for each opposite bars. The value of z depends if the winding function calculated is for a whole phase or a single parallel winding. In the first case z equals 1/a while in the other it's worth 1.

In summary, the winding function for a whole phase is:

$$n_x(k) = n_x(k-1) + z \text{ for k = 1 to N\_slot and } z = \begin{cases} 1/a \text{ for positive bars} \\ -1/a \text{ for negative bars} \\ 0 \text{ otherwise} \end{cases}$$

and for a single windings:

$$n_x(k) = n_x(k-1) + z \text{ for k = 1 to N\_slot and } z = \begin{cases} 1 \text{ for positive bars} \\ -1 \text{ for negative bars} \\ 0 \text{ otherwise} \end{cases} .$$

Exemple of winding functions are given below for the precompiled models.

5.3.4 Inductance calculations

Once all winding functions *n* for a specific machine are available, the various inductances can be computed according to the following formula

$$L_{yx} = L_{xy} = k_0[\langle n_x n_y \rangle - \langle n_x \rangle \langle n_y \rangle] - k_2[\langle n_x n_y \cos(2p\theta) \rangle - \langle n_x \rangle \langle n_y \cos(2p\theta) \rangle - \langle n_y \rangle \langle n_x \cos(2p\theta) \rangle]$$

where k_0 and k_2 are geometrical coefficient obtained from electrical parameters and intermediary inductance calculations; $\langle X \rangle$ is the expected value of X; p the number of pole pairs and θ the rotor electrical angle.

The inductances can be expressed in a more convenient form:

$$L_{yx}(\theta) = L_{xy}(\theta) = L_{yx0} + L_{yx1}\cos(2p\theta) + L_{yx2}\sin(2p\theta) \,.$$

L_{yx0}, L_{yx1} and L_{yx2} are computed before the simulation. This expression could be further reduced to a single trigonometric function with a phase term but its computational cost is quite high for faulty machines with numerous parallel windings.

5.4 Parameter Set Example

Two full parameter sets are shown in the following table as well as the original standard parameters. The conversion was done using Canay's work.

Table 5–1 : Generic 4-pole turbo-alternator and 48-pole hydraulic generator models parameters

Parameters	Turbo-alternator	Hydraulic generator
Type	Round	Salient
S_{base} (MVA)	675	370
V_{baseLL} (kV)	24	13.8
w_b (rad/sec)	120π	120π
Xls (pu)	1.3372e-1	1.5723e-2
Xmd (pu)	1.9633	9.6928e-1
Xmq (pu)	1.8363	5.9328e-1
Xlkq1 (pu)	2.0543e-1	4.5117e-1
Xlkq2 (pu)	1.0138	N/A
Xlfd (pu)	3.0335e-1	4.8771e-1
Xlkd (pu)	3.8567e-1	8.3011e-1
Rs (pu)	1.8300e-3	2.6360e-3
Rkq1 (pu)	2.4457e-2	1.9789e-1
Rkq2 (pu)	3.0294e-2	N/A
Rfd (pu)	5.6863e-4	5.2903e-4
Rkd (pu)	5.1693e-2	4.0598e-2
Rg (Ω)	500	500
H (pu.s)	2.5	4.1

Table 5–1 : Generic 4-pole turbo-alternator and 48-pole hydraulic generator models parameters

Parameters	Turbo-alternator	Hydraulic generator
F (pu)	0	0
P	4	48
N_slot	60	540
N_cs	2	2
N	2	6
Standard parameters		
Rs (pu)	0.00183	0.002636
Xls (pu)	0.215	0.015
Xd (pu)	2.097	0.985
Xd’ (pu)	0.395	0.340
Xd" (pu)	0.29	0.249
Xq (pu)	1.97	0.609
Xq’ (pu)	0.643	0.60
Xq" (pu)	0.29	0.272
Tdo’ (s)	10.661	7.348
Tdo" (s)	0.033	0.075
Tqo’ (s)	0.415	N/A
Tqo" (s)	0.056	0.14

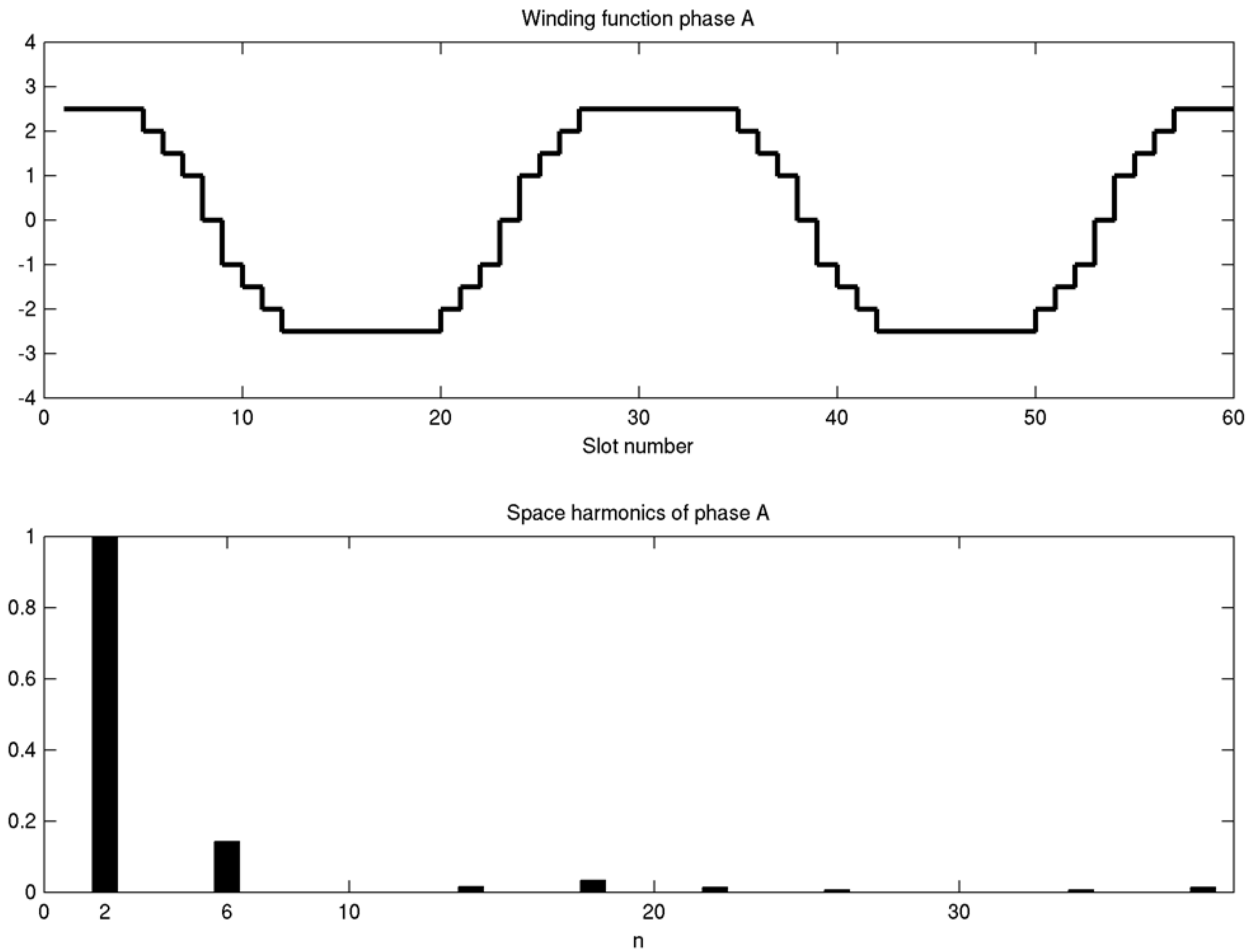

Figure 5 - 3   Winding function for phase A (A1 and A2 winding) of generic turbo-alternator

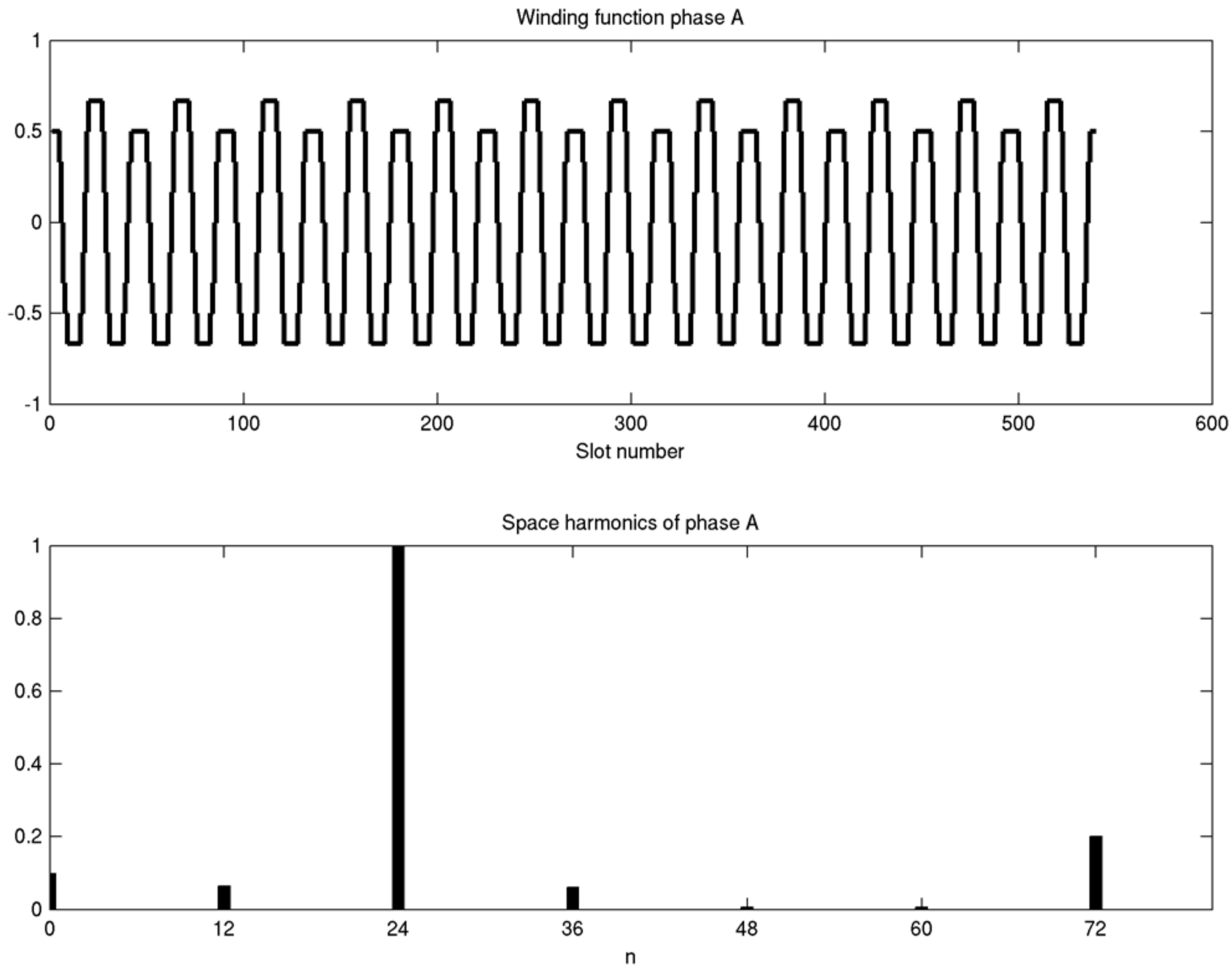

Figure 5 - 4   Winding function and its spectral analysis for phase A (A1 to A6 winding) of generic hydraulic generator

5.5 INTERNAL FAULTS

As mentionned earlier, this model supports eight types of stator internal faults. Each one will be detailled in the following sections.

The location of the fault is specified in percents, where 0% is the neutral point and 100% is the terminal of the particular phase.

5.5.1 Type 1: Single Winding to ground

In this type of fault, one winding is shorted to the ground through a resistor Rfg as shown in the following schematic (rotoric circuit and windings' resistance not illustrated). The faulted winding is separated in two parts, A_{f1} and A_{f2}. The same is also true for the related winding function. The two resulting winding functions are then used to calculate A_{f1} and A_{f2} self and mutual inductances.

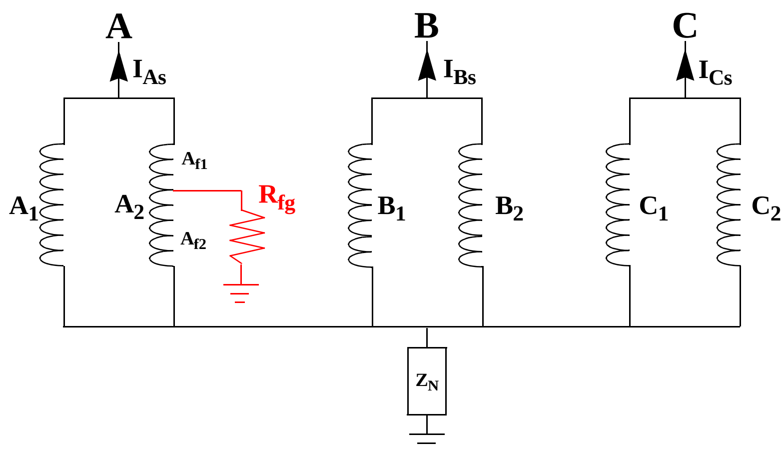

Figure 5 - 5 Type 1 fault in a synchronous machine with two parallel windings and neutral impedance

During healthy behavior, R_{fg} must be very large (> 1e6 pu) and to trip the faulty behavior, it has to be stepped down to a very small value. This mechanism is valid for all types of fault.

$$i_{faultT1} = i_{af1} - i_{af2}$$

$$i_{ain} = i_{a1} + i_{af1} \qquad i_{aout} = i_{a1} + i_{af2}$$

$$i_g = i_{aout} + i_{b1} + i_{b2} + i_{c1} + i_{c2}$$

5.5.2 Type 2 & 3: Phase-Phase Shorted Windings (to ground)

Two windings from different phases are shorted together through two resistors, R_{fa} and R_{fb} and the mid point is grounded through R_{fg}. A type 2 fault is when the mid point remains ungrounded, i.e. R_{fg} stays very large during the fault, while a type 3 implies very small values for all three resistors for the duration of the fault. These two types of stator internal faults are treated together since they affect the winding functions the same way. As illustrated by Figure 5 - 6, both faulty windings are treated as an upper and lower part separated by the fault point.

$$i_{faultT2} = i_{af1} - i_{af2}$$

$$i_{faultT3} = i_{af1} + i_{bf1} - i_{af2} - i_{bf2}$$

$$i_{ain} = i_{a1} + i_{af1} \qquad i_{aout} = i_{a1} + i_{af2}$$

$$i_{bin} = i_{b1} + i_{bf1} \qquad i_{bout} = i_{b1} + i_{bf2}$$

$$i_g = i_{aout} + i_{bout} + i_{c1} + i_{c2}$$

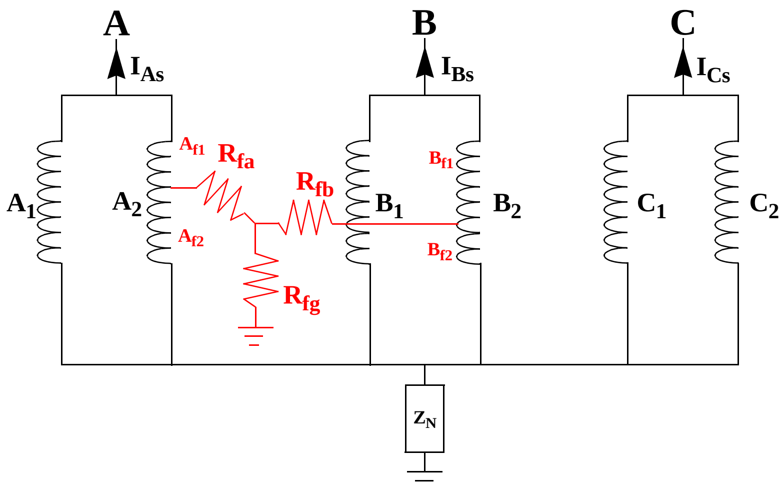

Figure 5 - 6 Type 2 and 3 fault in a synchronous machine with two parallel windings and neutral impedance

5.5.3 *Type 4 & 5: Three-Phase Shorted Windings (to ground)*

Very similar to type 2 and 3, this fault type also involves a winding from the remaining phase. A type 5 fault involves a small R_{fg} while type 4 does not. Type 4 fault current is arbitrary set as the current flowing through Rfa.

$$i_{faultT4} = i_{af1} - i_{af2}$$

$$i_{faultT5} = i_{af1} + i_{bf1} + i_{cf1} - i_{af2} - i_{bf2} - i_{cf2}$$

$$i_{ain} = i_{a1} + i_{af1} \qquad i_{aout} = i_{a1} + i_{af2}$$

$$i_{bin} = i_{b1} + i_{bf1} \qquad i_{bout} = i_{b1} + i_{bf2}$$

$$i_{cin} = i_{c1} + i_{cf1} \qquad i_{cout} = i_{c1} + i_{cf2}$$

$$i_g = i_{aout} + i_{bout} + i_{cout}$$

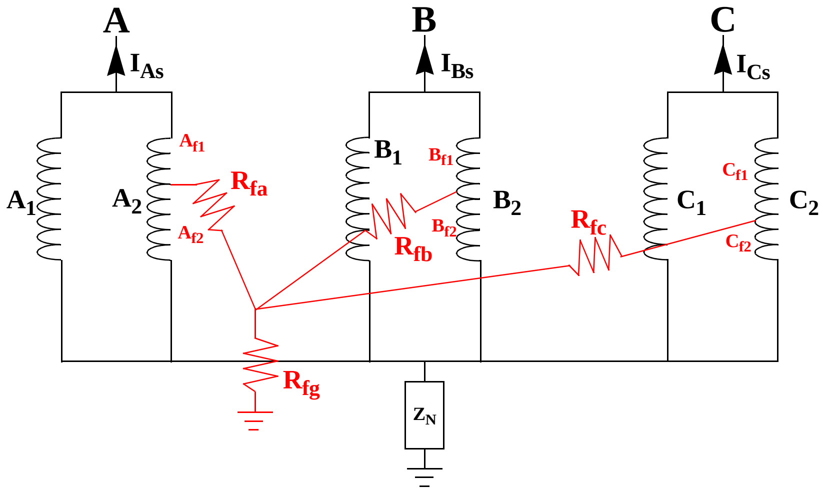

Figure 5 - 7 Type 4 and 5 fault in a synchronous machine with two parallel windings and neutral impedance

5.5.4 Type 6 & 7: Single Phase Shorted Windings (to ground)

Similar to type 2 and 3, this internal fault is between two windings of the same phase. To realize a type 6 fault (winding-winding), R_{fg} must be kept very large during the fault while a type 7 fault, winding-winding-ground, the grounding resistor must be stepped down to a small value.

$$i_{faultT6} = i_{af1} - i_{af2}$$

$$i_{faultT7} = i_{af1} + i_{af3} - i_{af2} - i_{af4}$$

$$i_{ain} = i_{af1} + i_{af3} \qquad i_{aout} = i_{af2} + i_{af4}$$

$$i_g = i_{aout} + i_{b1} + i_{b2} + i_{c1} + i_{c2}$$

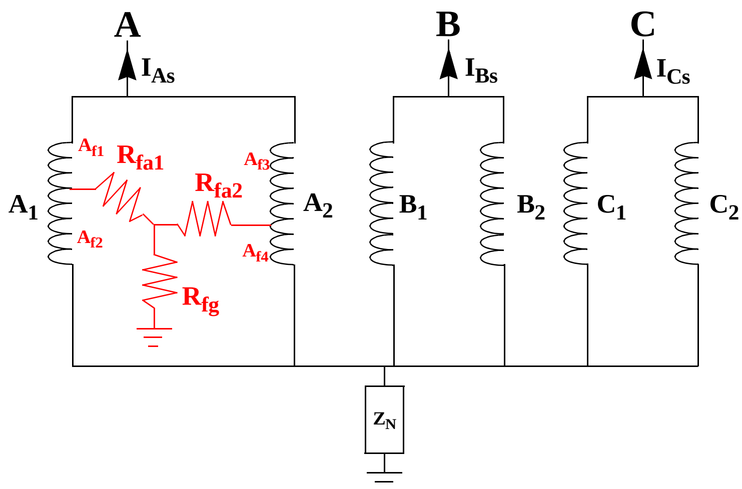

Figure 5 - 8 Type 6 and 7 fault in a synchronous machine with two parallel windings and neutral impedance

5.5.5 *Type 8: Single Winding Shorted turns*

This type of fault involves only one winding where a number of turns are shorted. That particular winding is splitted in three sub-windings, as shown in Figure 5 - 9, but, mathmatically, it's treated as two since the same current, i_{af1}, flows through A_{f1} and A_{f3}.

$$i_{faultT8} = i_{af1} - i_{af2}$$

$$i_{ain} = i_{aout} = i_{a1} + i_{af1}$$

$$i_g = i_{aout} + i_{b1} + i_{b2} + i_{c1} + i_{c2}$$

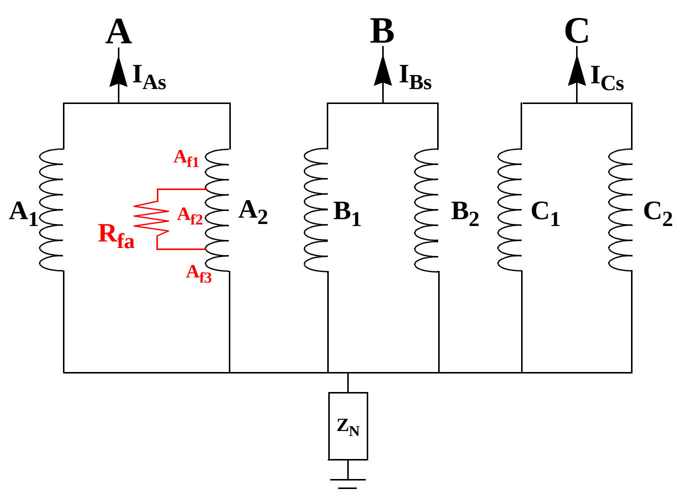

Figure 5 - 9 Type 8 fault in a synchronous machine with two parallel windings and neutral impedance

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