Symptoms of Mechanical Faults Deduced from Analysis of Electrical Power Supply

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Abstract-An output mechanical power of electrical driving system is directly related to electrical power consumption; proportional relation. This direct relation is a foundation of concluding of failures, manufacturing imperfections, wear and tear of gears used in driving systems. The paper is devoted to consideration how to investigate abnormal mechanical states caused by mechanical parts (gears in this case) of driving system based on analysis of consumed electrical power. Driving systems for power transmission are using different gears boxes (reducers and multipliers), mainly are helical gear boxes. Most of gear use wheels with "teeth". Shapes of teeth are no perfectly identical due to imperfection of mechanical treatment at the production process. As a result of long time of gear box running, teeth are loosing their original shapes. Cracks may arise and even tooth or teeth may be broken. Such situation should be predicted before gear box fail down. The symptoms of such situation are analysed in the paper. The uncertainty analysis is a key for successful deduction about the state of gear.

1. Impulses of mechanical power as result of mechanical defects

Gear boxes and frequency converters are used in driving systems to adjust torque and speed according to applications. The faults of gear boxes caused at the stage of production or during normal operation of the system are critical for operation, so it is important to predict such faulty situation in order to replace element.
The most frequently faults in gear boxes are: (i) broken tooth (ii) radial run-out (iii) deviation in contact line due to imperfection in teeth shape and obliquity of action.
The kinematical schema of gear with toothed wheels is presented in Fig 1.

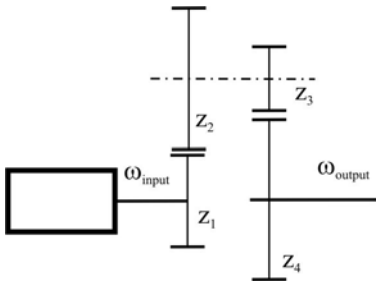

Fig 1. Kinematical schema of gear with toothed wheels z1, z2, z3, z4 number of teeth of gear wheels.

In the case of damaged of tooth of the wheel 2 frequency f_{i2} of generated torque is given by Equ 1

$$f_{i2} = \omega_2 \cdot z_2 = \omega_{input} \cdot z_1 \tag{1}$$

The power of geared mechanical impulses is :

$$P_{i2} = M_{i2} \cdot \omega_{i2} = M_{i2} \cdot \omega_{input} \frac{z_1}{z_2} \tag{2}$$

2. Electrical impulses in power consumption of motor caused by impulses of mechanical

Momentary changes of torque at the shaft of electrical motor reveal themselves in electrical power consumption of the motor joint with gear. It this torque variation is a result of imperfection of gear manufacturing production like geometrical imperfections, wear and tear are resulting in electrical power consumption at the input of electrical drives.
Two type of electrical drives can be distinguish:

- with speed control elements (called non-linear system) and
- non-speed control elements (called linear system)

These two cases are in Fig. 2 and Fig 3, which are very similar each other from the point of view symptoms, of wear and tear and imperfection or coming malfunctioning states of gears.

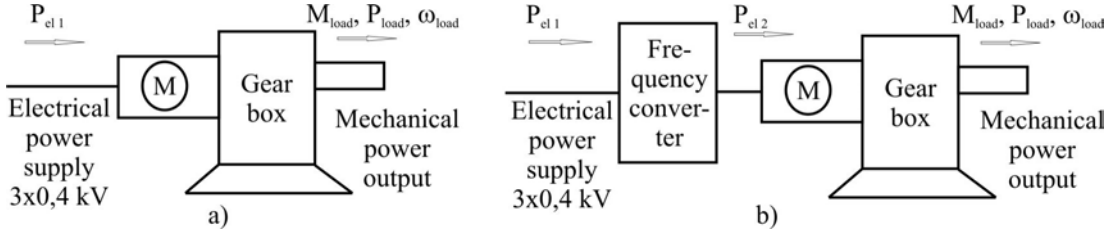

Fig 2 Two driving systems: a) non speed controlled b) speed controlled by frequency converter

For furter analysis of harmonic appearance at system with frequency converter (Fig.2b)we hale to destinguish two circuitries:

- input circuitry, which consists of rectifiers part and intermediate circuitry,
- output circuitry, which is connected to electrical motor.

The input circuitry is connected to power supply, output to electrical motor and the element between them is - so called DC bus of which one of the element is a coupling capacitor.

Voltage appearing on DC bus is chopped into pulses, in fact, it is a pulse train with a modulated duty cycle and amplitude, if modified Pulse Width Modulation, PWM, method is applied. The pulse trains of 3 phases appearing at the input of motor are causing flux in motor, which is proportional to required output motor torque.

Harmonic content at the input of motor contains fundamental harmonic, of which frequency is proportional to actual motor rotational speed, and other harmonics. The other harmonics are bearing information about carrier frequency of pulse components related to physical changes by torque, which is due to malfunction of gear and geometrical imperfection of elements of gear box joint to electrical motor.

The paper is devoted how to analysis current – which are related to symptoms of damages of gears.

Electrical equivalent diagram , which represents scheme of Fig 2 b) is presented in Fig.3

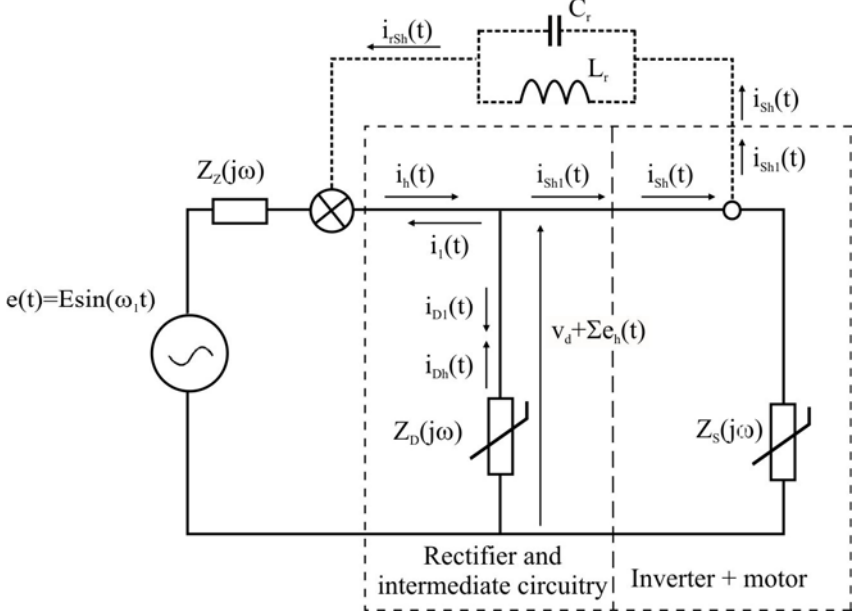

Fig. 3. Equivalent electrical scheme representing non-linear system (Fig. 2b) frequency converter and motor used for identification of symptoms of manufacturer imperfections or faults in gears

E, ω_1- amplitude and angular frequency of power supply

$Z_Z(j\omega)$-impedance of supply lines and internal impedance of supplying source

$Z_D(j\omega)$- impedance representing (rectifier and intermediate circuitry of inverter)

$Z_S(j\omega)$ – impedance of output inverter circuitry and electrical motor.

C_r – coupling capacitance,

L_r- mutual inductance output circuitry of inverter and power supply

$i_1(t)$ – inverter current supply (1 st harmonic)

i_{D1}- current through capacitor of intermediate circuitry (1-harmonic)

$i_{s1}(t)$ – current through motor (1-harmonic)
$i_h(t)$ – higher harmonic components of current generated by frequency converter at the input.
$i_{sh}(t)$ - higher harmonic components of current at the input to electrical motor generated by frequency converter due to used method of frequency converter (PWM)
$ir_{Sh}(t)$ - higher harmonic components of current generated by frequency converter at the input
V_d – voltage – DC (DC voltage at the capacitor of interchangeable circuitry

$\sum_h e_h(t)$ DC bus harmonic content expressed as: $\sum_h e_h(t) = \mathrm{Im}\left[\sum_h Z(jh\omega)\cdot i_{Dh}(jh\omega)\right]$

For furter analysis of harmonic appearance At the input of frequency converter it is convenient to distinguish two parts of also represented in Fig. 3

1. input circuitry, which consists of rectifiers part and intermediate circuitry,
2. output circuitry of which functional result is a and out voltage and current supplying electrical motor; this part is full controlled by control circuitry according to desired frequency and voltage needed to control motor.

The input circuitry is connected to power supply, output to electrical motor and the element between them is so called DC bus of which one of elements is a coupling capacitor.
Voltage appearing on DC bus is chopped into pulses in fact it is a pulse train with a modulated duty cycle and amplitude if Pulse Width Modulation,, PWM, method is applied. The pulse train – in fact 3 phases of continuously appearing pulses appearing at the input of motor are causing flux in motor, which is proportional to required output motor torque.
Harmonic content at the input of motor contain fundamental harmonic, of which frequency is proportional to actual motor rotational speed, and other harmonics. The other harmonic are bearing information about carrier frequency of pulse train and other in which one component can be related to physical changes due to malfunction of geometrical imperfection of elements of gear box connected to output of the motor.
A complete block diagram of the testing gears's set-up is presented in Fig. 4.

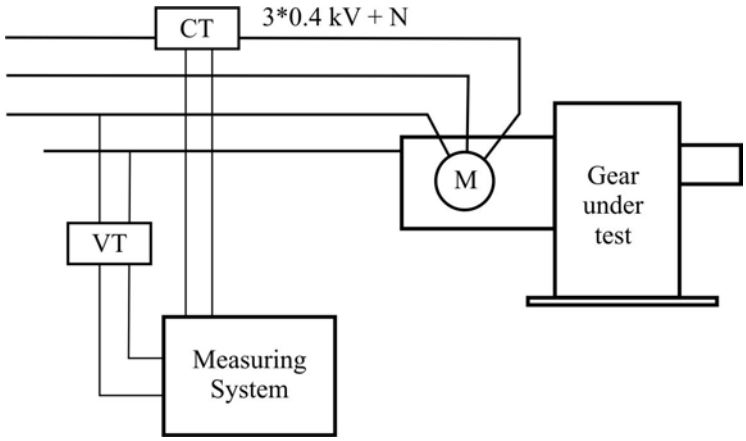

Fig 4. Complete testing set-up in which: CT – Current transformer, VT Voltage transformer, M- electrical motor,

Also for scheme in Fig. 2a we have to remember to take into account the nonlinearity of input current. It is a factor, which is not helping us to analyse the distortion of current due to geometrical changes of teeth of gears. The voltage is given by:

$$v(t) = v_1(t) + \sum_h v_h(t) \tag{3}$$

where:

$v_1(t)$ - time representation fundamental harmonic in voltage

$v_h(t)$ - time representation higher harmonics of voltage

In the case of scheme presented in Fig 2b in which motor is supplied via inverter from power net, the Voltage transformer is connected to DC bus of inverter as it is presented in Fig. 5.

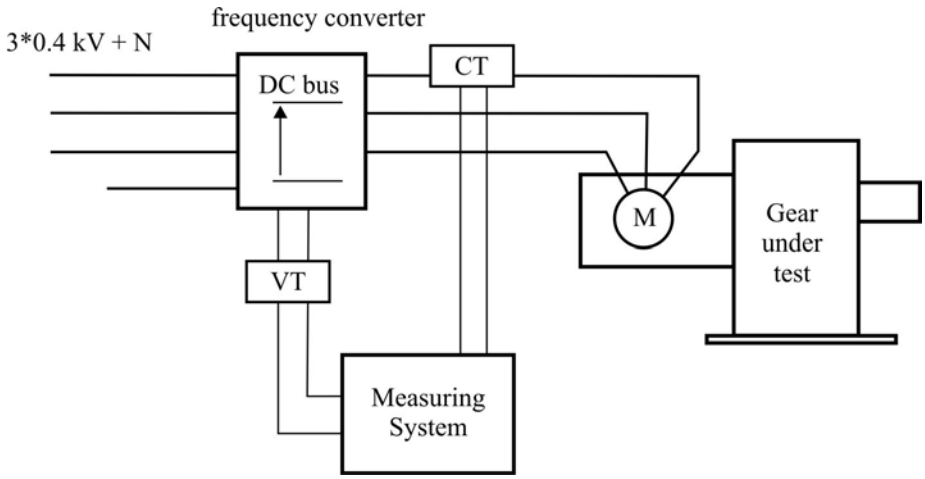

Fig. 5. Measuring set-up to identify impulse or distortion caused by „gear" in the case of supplying motor via frequency converter.

Measurement of impulse induced by failures in gears.
For both cases presented in Fig 2 the momentary electrical power is measured as a result of product of voltage and current of samples At the input of motor (Equ. 4):

$$p(k) = i(k) \cdot v(k) \tag{4}$$

where:
$i(k)$ - sample of motor current, $v(k)$ -sampled voltage of motor k - th sample
sampling frequency must apply to the rule that higher then doubled frequency of highest expectable frequency and also aliasing effect must be avoid.

The proper analysis of current coming from faults in gear need: firstly the harmonics induced due to motor nonlinearity itself and secondly frequencies induced by frequency converter have to be eliminated. This a base for later deliberation of shape of electrical power as a result of joint gear to the motor. It is a very challenging task from measurement point of view.

III. Conclusions

The investigation of symptoms of malfunctioning in gear boxes of systems without frequency converters were performed at the power supply side and in the current consumed by electrical motor is frequency converters are used.

In the case of linear system impulses generated due to mechanical failures are transformed directly to electrical power net as current distortion at the input of electrical motor. The electrical momentary power consumption is effected by this mechanical phenomena.

In the case of non-linear system the mechanical failures are effecting power consumption between motor and inverter and the effect is observed at momentary current consumption at the inverter DC bus.

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