RESEARCH PAPER

Reducing the effect of total harmonics distortion of synchronous machines

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A B S T R A C T:

Synchronous machines have a great role in power system generation and controlling, reducing harmonics have been a major concern of researchers, especially with the increasing of electronic equipment and automated controls in addition to use of nonlinear loads in power systems all of these increase additional harmonic generated. In this paper various parameters were investigated such as air gap length, rotor width, rotor diameter, (pole arc / pole pitch) in order to minimize the effect of total harmonics distortion of synchronous machine by utilizing of MATLAB program.

1.INTRODUCTION :

The expected waveform of a synchronous generator is sinusoidal wave but unfortunately many of undesirable waveforms (harmonics) contained in the waveform due to many reasons, the result is a distortion of the fundamental waveform. The main goal of all researchers is to decrease the effect of these harmonics, which are multiples of the fundamental basic frequency.

IEEE defines harmonic content as "a measure of the existence of harmonics in a voltage or current waveform expressed as a percentage of the amplitude of the fundamental frequency at each harmonic frequency Fig.1

The harmonics can be minimized, but it is not an easy because the air gap has maximum reluctance to the flux path due to which air gap cannot be sinusoidal, if the air gap is made to be sinusoidal around the machine, then wave form would be sinusoidal and total harmonics would be minimized. But wave field form cannot be sinusoidal due to magnetic saturation in iron parts and hence can decrease them [Rakesh & Pande 2013].

Currently, the common sources of harmonics are power electronic loads such as variable speed drives also the harmonics increasing with use of nonlinear loads such as wave rectifiers, static compensator such as SVC, and electronics controlled devices and switching mode power supplies. These loads use diodes, silicon-controlled rectifiers, power transistors, and other electronic switches used to chop waveforms to control power or to converts A.C. voltage to D.C. voltage. In the case of variable speed drive , the D.C. voltage is converted to variable-frequency A.C. voltage to control motor speed. Such in chillers and pumps. Also Flexible Alternating

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Current Transmission System (FACTS) used to improve power quality considered as nonlinear and complex as compared to mechanical switches [William ,2001, Holey & Chandrakar,2016].

The principle of how the harmonic components are added to the fundamental current is shown in Fig.2, where only the 5th harmonic is shown.

2. LITERATURE REVIEW

Many researchers began to search about harmonics since 19th century and their effects [Emanuel, 2000]. it was known that the connection of the windings at the terminals of a alternator can cancel some harmonics according to the connection of windings, for instance when star connection is used then the third harmonic and its multiples are cancelled while the neutral is kept ungrounded also in a delta-connected generator the third harmonic current creates additional heat losses [Eden, 1914]. In 1924 special design can significantly affect the power quality in synchronous generator due to the shape of the salient poles. This technique has been implemented on the early type of generators [Hague, 1924]. However it still represents a popular optimization design process, as demonstrated by more recent literature [Wang et al., 2017].

Stator winding chording, rotor skewing, and stator slots are factors effecting on the torque developed, power factor, and torque ripple of a reluctance synchronous machine by using the two dimensional finite element time method used by [Xola & Kamper ,2002].

Another method used to get optimum design of slotted axial flux internal stator motor by using new genetic algorithm [Gholamian et al.,2011].

Also another method used by selecting the proper air gap length and analyzes the effect of air gap changes on the performance of a three-phase axial flux synchronous generator, including how the gap affects the generator's performance

Also sensitivity analysis used to obtain optimum design parameter along with signal-to-noise ratio results [Azizi & Abolfazal, 2015].

Another method used by authors is to make comparison of higher harmonic contents in salient pole synchronous generator voltage waveform with different rotor construction [Krzyszt et al., 2017].

Another new winding pattern for stator of the synchronous generators is presented by Hossein & Beromi to eliminate the harmonic contents of output voltage to makes it more sinusoidal. [Hossein & Beromi , 2017]. Finally Daniel and his follows presented a review of conventional power quality improvement measures at generation level. The main focus is on total harmonic distortion (THD) improvements, where the main techniques and methodologies implemented onto electrical machines over the last century and a half [Daniel et al., 2018].

3. HARMONICS RESULTS

Unlike transient events such as lightning that last for a few microseconds, or voltage sags that last from a few milliseconds to several cycles, harmonics are steady-state periodic phenomena that produce continuous distortion of voltage and current waveforms [Hossein & Yousef, 2017].

Harmonics in power systems can cause network resonation for defined harmonic that can expose equipment of power system to higher strain by overvoltage or overcurrent, overheating and overloading which causes reduction in the efficiency and age of transmission, distribution and compensation devices. Also harmonics causes incorrect functionality of electric protection, interference of telecommunication devices & incorrect functionality of control circuits. Among the possible external effects of harmonics are degradation in communication systems performance, excessive audible noise and harmonic-induced voltage and currents. [Jos, 2004, Gholamian et al.,2011].

4. HARMONICS ANALYSIS

The widely used method of measuring of distortion is total harmonic distortion (THD). The total harmonic distortion is used to define the effect of produced harmonics on the waveform voltage. It can be used in low-voltage, medium-voltage, and high-voltage systems. The expression of total harmonics distortion is defined as : [Jos, 2004]

$$\text{THD}\% = \left(\frac{\sqrt{V2^2 + V3^2 + V4^2 + \cdots + Vn^2}}{V1}\right) * 100 \qquad (1)$$

Where Vn is the voltage of the nth harmonic and n = 1 is the fundamental frequency.

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Total harmonic distortion applies to both current and voltage and is defined as the r.m.s value of harmonics divided by the r.m.s value of the fundamental, and then multiplied by 100%. THD of current varies from a few percent to more than100%. THD of voltage is usually less than 5%. Voltage THDs below 5% are widely considered to be acceptable, but values above 10% are definitely unacceptable and will cause problems for sensitive equipment and loads [Hossein & Yousef, 2017].

The analysis of modeled excitation field performed using fast Fourier transformation. Obtained results show both important factors of designed winding – the magnitude of fundamental harmonic component H and the volume of higher order harmonic components, which may be expressed in form of total harmonic distortion (THD).

For known value of intensity of magnetic field in the air gap a proportional expression of fundamental harmonic component magnitude may be introduced as a ratio

$$h = \frac{H_l}{H_\delta}[\text{p.u.}] \qquad (2)$$

Where H_l is the magnitude of fundamental harmonic component obtained from the fast Fourier transform FFT and H_δ is desired value of air gap magnetic field strength.

The value of Hδ is then derived from known value of air gap's magnetic flux density B using known permeability of the air μo

$$H = \frac{B_\delta}{\mu_o}[\text{p.u.}] \qquad (3)$$

A suitable expression of generated magnetic field's quality is the total harmonic distortion ratio based on power/energy definition, especially because of its identity with expression of differential leakage flux coefficient. Using results obtained from the Fourier analysis the THD of excitation winding is

$$THD = \frac{\sum H_v^2 - H_l^2}{H_l^2} \ [\text{p.u.}] \qquad (4)$$

Where Hv is the magnitude of ν-th harmonic component. As an optimal result the designed winding should include possibly lowest amount of higher order harmonic components and the magnitude of air gap's magnetic field intensity's fundamental harmonic component of designed winding should be equal to its requested value. Thus, the value of THD should by near to zero

and the value of H_l should be near to one [Karel et al., 2014].

5. CONCEPT OF DISTORTION WAVEFORMS

There are three methods used for analysis of harmonics time domain, direct frequency domain and iterative techniques. The analysis of the distorted waveform allows us to express the distorted waveform as a sum of dc component, fundamental sine wave of the distorted waveform and series of pure sine waves .These sine waves have different magnitudes and their frequencies are integer multiple of the fundamental distorted waveform. This expression is called Fourier series representation. A distorted waveform can be analyzed using Fourier series representation applies following equations [Jos,2004, William & Surya,2001]

$$X(t) = a_0 + \sum_{n=1}^{\infty}(a_n \cos(n\omega t) + b_n \sin(n\omega t)) \qquad (5)$$

Where
$$a_0 = \frac{1}{T}\int_0^T X(t)d(t) \qquad (6)$$
$$a_n = \frac{2}{T}\int_0^T X(t)\cos(n\omega t)d(t) \qquad (7)$$
$$b_n = \frac{2}{T}\int_0^T X(t)\sin(n\omega t)d(t) \qquad (8)$$
n=1,2,3,……….

6. RESULTS

In this paper salient pole synchronous generator of 100 MVA , 13.2 kV examined as a model with different parameters change is taken to obtain optimum values of such parameters which effect in decreasing the harmonic distortion of the waveform.

Tab.1 shows the effect of increasing of the air gap length on the distortion (THD%) with the rotor diameter length of 0.15 Inch with load of 0.8 p.f. lag.

From Tab.1, it can be noticed that the optimum air gap length of this case is 0.15 inch in which THD% will be 7.2596%, table 2 shows the effect of increasing the rotor diameter and THD% in the case of air gap length of 0.1 inch.

From Tab.2, it can be noticed that the increasing of the rotor diameter will result increasing of the distortion. Table 3 shows relation between (pole arc /pole pitch) versus THD%.

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From Tab.3, it can be noticed that optimum THD% can be obtained when the (pole arc / pole pitch) is 0.8. Tab.4 shows the relation between rotor width and THD%.

From Tab.4, it is noticed that the THD% increases with the increase of the rotor width.

From figures, it can be noticed that the magnetic waveform is distorted with the increasing of the air gap length and the harmonics significantly produced.

7. CONCLUSIONS

The analysis of the results show that the total harmonic distortion THD% decreases with the increasing of each of the air gap length & (pole arc /pole pitch) ratio (till reach the optimum values), and continuously decreases with the rotor width while THD% increases with rotor diameter, as known larger rotor means more flux distribution which results more distortion. Also the all types of harmonic contents in the magnetic flux density in the air gap (calculated during simulations in the Matlab program) decreases and in the voltage waveforms induced in the stator winding.

The slot harmonic e.m.f can be drastically reduced and even completely eliminated from output voltage waveform by using optimum design parameters.

The decreasing the total harmonics distortion effects on the performance of a synchronous generator, including the synchronous generator's efficiency, current, power factor and voltage induced.

Optimum air gap is a very important parameter because it greatly affects the performance of the machine. Air gap in synchronous machine affects the value of short circuit current and hence it influences many other parameters. Hence, choice of air gap length is very critical in case of synchronous machines.

From the results it can be noticed that the optimal air gap length can be obtain Fig.4, with minimum harmonic spectrum Fig.5, corresponding with the highest efficiency with best power factor of the machine.

The larger the air gap, the larger slot harmonic e.m.f Fig.5,7&9, and higher harmonic spectrum increases Fig.6,8&10, the higher the current is that

passes through the load with the lower of efficiency due to the losses and the temperature rise in the machine.

Table (1). Effect of increasing of air gap length to THD% of D=0.15inch at 0.8 p.f. lag.

Air gap length (inch)	Distortion THD%	Air gap length (inch)	Distortion THD%
0.1	11.8309	0.155	7.3137
0.1025	11.3644	0.16	7.4348
0.105	10.9233	0.17	7.8368
0.1075	10.573	0.18	8.3876
0.11	10.1163	0.19	9.0291
0.115	9.4096	0.2	9.7195
0.12	8.8036	0.21	10.4313
0.13	7.8965	0.25	13.231
0.14	7.3921	0.30	16.3218
0.145	7.2827	0.35	18.9282
0.15	7.2596	0.45	23.0356

Table (2). Relation of rotor diameter D and the THD% at 0.8 p.f. lagg. with air gap length of 0.1 Inch

Rotor D (inch)	Distortion THD %	Rotor D (inch)	Distortion THD %
10	7.2596	17	14.3771
11	7.5301	18	15.6194
12	8.2991	19	16.83
13	9.3594	20	18.0061
14	10.5652	22	20.2521
15	10.8309	25	23.3675
16	13.1099	30	27.9756

Table (3). Relation between (pole arc /pole pitch) and THD%

(Pole arc/pole pitch)	THD%	(Pole arc/pole pitch)	THD%
0.1	36.4437	0.6	11.5563
0.2	31.8335	0.7	7.1495
0.3	26.7805	0.8	6.4865
0.4	21.8413	0.9	10.5314
0.5	16.5855	1	15.688

Table (4). Relation between Rotor width and THD%

Rotor Width (inch)	THD%	Rotor Width(inch)	THD%
2	16.1085	7	12.2225
3	15.3386	8	11.4623
4	14.2874	9	10.9777
5	13.5555	10	10.5709
6	12.8667	11	10.2574

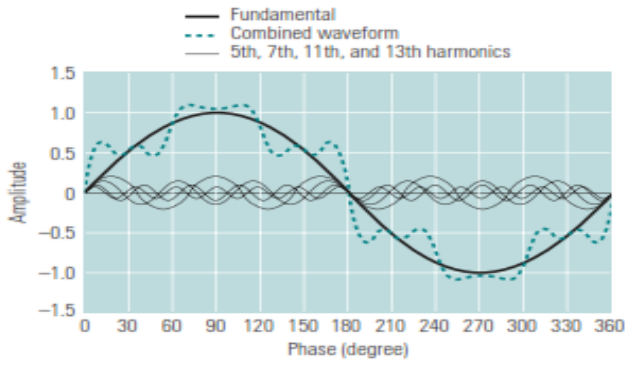Ahmad. H. and Akram. A. /ZJPAS: 2019, 31 (s3): 373-379

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Figure 1. Effect of harmonics on normal voltage or current wave form.
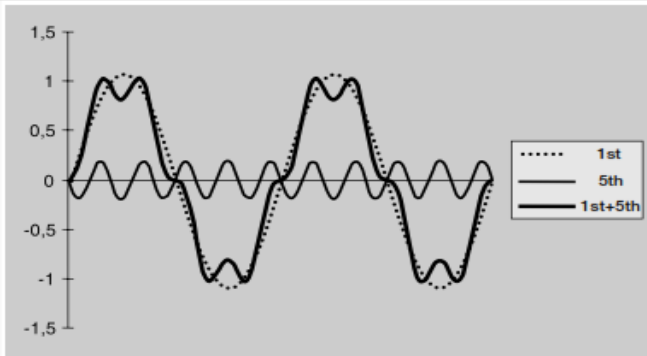

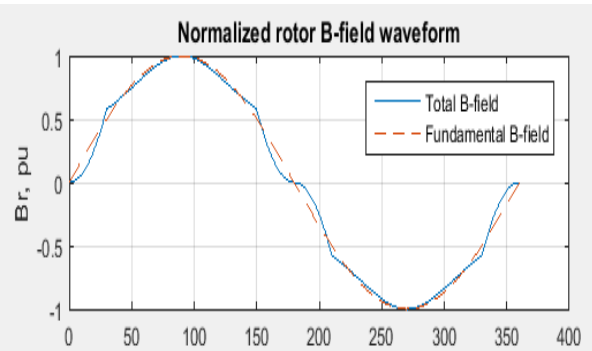**Figure 2.** The total current as the sum of fundamental and 5th harmonic.

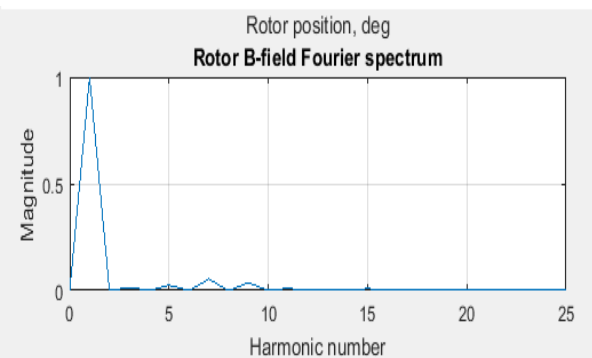**Figure. 3** Magnetic field waveform air gap length is 0.15 inch
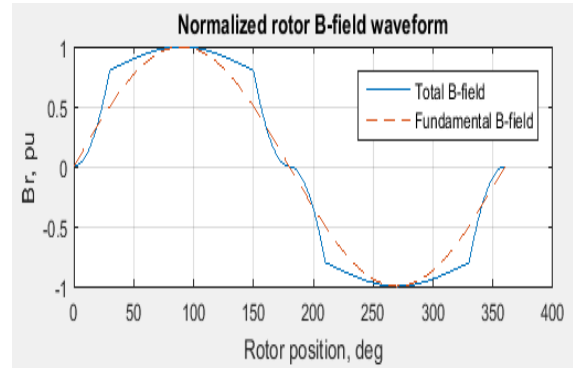

Figure. 4 Harmonics magnitude of air gap is 0.15 inch

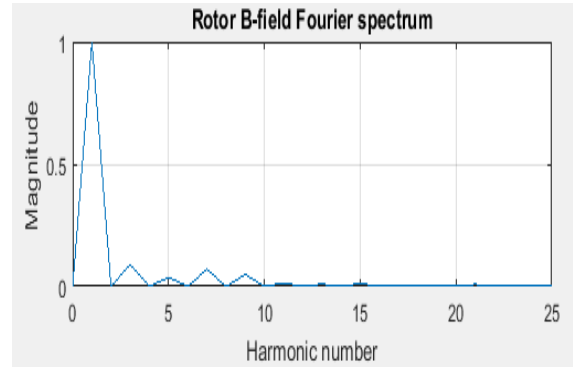**Figure. 5** Magnetic field waveform air gap length is 0.25 inch
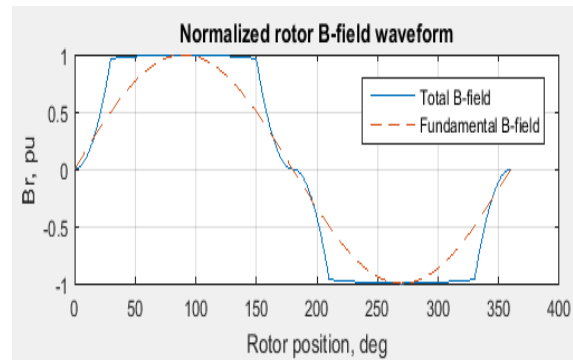

Figure. 6. Harmonics magnitude of air gap =0.25 inch

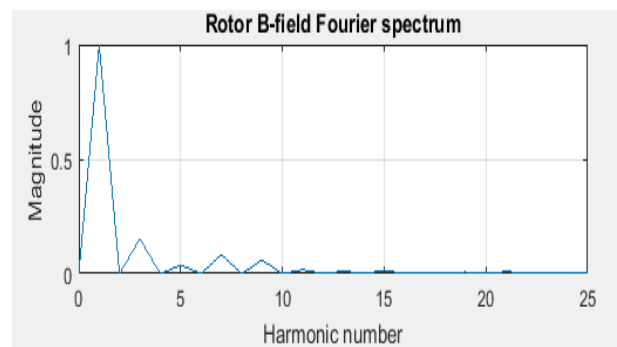**Figure. 7** Magnetic field waveform air gap length is 0.35 inch

Figure. 8. Harmonics magnitude of air gap is 0.35 inch

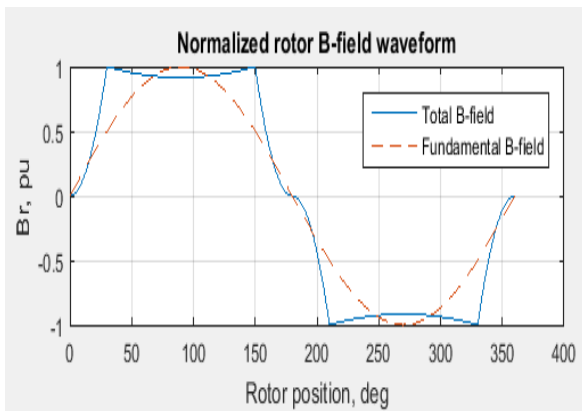Ahmad. H. and Akram. A. /ZJPAS: 2019, 31 (s3): 373-379

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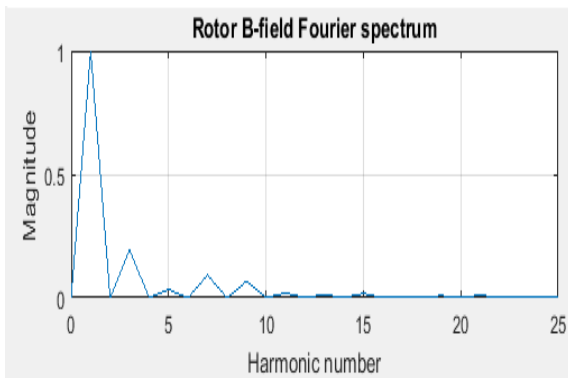**Figure. 9** Magnetic field waveform air gap length is 0.45 inch

Figure. 10 Harmonics magnitude of air gap is 0.45 inch

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Apendex

Part of the program (harmonic M-file).

```
=13200; S=100e6;  Xs=6.94; Rs=0.15; p=2;  S2=20;  bf=2; Dr=41;VL
theta=[acos(0.8) acos(1) -acos(0.8) ];
IR=S/sqrt(3)/VLR;
VL=[]; IL=[];
for n=1:length(theta);
Ef=abs( VLR/sqrt(3)+IR*exp(-j*theta(n))*(Rs+j*Xs));
ZLR=VLR/sqrt(3)/IR*exp(j*theta(n));
ZL=linspace(0.5*ZLR,2*ZLR,1000);
 for i=1:length(ZL)
 Ia(i)=Ef/abs(Rs+j*Xs+ZL(i));
 Va(i)=Ia(i)*abs(ZL(i));
 end
VL=[VL;sqrt(3)*Va]; IL=[IL;Ia];
end
 taur=pi*Dr/p; Wf=0.25*taur; nr=S2/2/p;
gam2=(pi*Dr-p*Wf)/2/Dr/nr; lamr=Dr/p*gam2;
nlamr=fix(gam2/2/pi*1024);nrmp=fix(bf/pi/Dr*1024);
if nrmp/2~=fix(nrmp/2); nrmp=nrmp-1; end;
mag=0; k=1;
for i=1:256
  if        (i==(2*k-1)/2*nlamr)&&(k<nr+1);        k=k+1;
mag=mag+1/nr;
  else end
  Ff(i)=mag;
k=1
for i=1:256
  if (i==(2*k-1)/2*nlamr)&&(k<nr+1); k=k+1;
    for j=i-nrmp/2+1:i+nrmp/2-1
     Ff(j)=Ff(i-nrmp/2)+1/nr/nrmp*(j-i+nrmp/2);
    end
Ff=[Ff fliplr(Ff)]; Ff=[Ff -Ff];
theta=linspace(0,360,1024);
x=abs(fft(Ff));
y=x(2)/512*sin(theta*pi/180);
subplot(2,1,1); plot(theta,Ff,theta,y,'--'); grid;
title('Normalized rotor B-field waveform');
xlabel('Rotor position, deg'); ylabel('Br, pu');
legend('Total B-field','Fundamental B-field',1);
subplot(2,1,2); plot([0:25],x(1:26)/512); grid;
title('Rotor B-field Fourier spectrum');
xlabel('Harmonic Number'); ylabel('Magnitude');
THD=0; for i=3:50; THD=THD+(Bf(i)/Bf(2))^2; end
THD=sqrt(THD)*100; disp(' ');
disp(['TOTAL    HARMONIC    DISTORTION(%)    = ',num2str(THD)]);
THD=0; for i=3:50; THD=THD+(x(i)/x(2))^2; end
THD=sqrt(THD)*100; disp(' ');
disp(['TOTAL    HARMONIC    DISTORTION(%)    = ',num2str(THD)]);
 n=length(ZL);
plot(IL(1,1:n),VL(1,1:n),IL(2,1:n),VL(2,1:n),'--',IL(3,1:n),...
VL(3,1:n),'-.', IR,VLR,'o',0,0); grid
```