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HARMONIC CONTENT IN THE VARIABLE-FREQUENCY AC POWER LINE OF TFTR

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Abstract

This paper describes studies of the harmonic content of the current and voltage at the generator bus of the Tokamak Fusion Test Reactor. Out of numerous load scenarios, one case was considered in detail. The harmonics were found acceptable for the generator; however, control problems and substantial telecommunications interference may result, requiring appropriate control measures and shielded telecommunications lines.

Introduction

The TFTR energy conversion system has four subsystems: the toroidal field (TF), equilibrium field (EF), ohmic heating (OH), and horizontal field (HF). Each subsystem is supplied by one or more converters. Each converter has two three-winding transformers supplied through a common circuit breaker and current-limiting reactance from a variable-frequency generator bus. The low-voltage windings of the transformers connect to three-phase bridge-connected thyristor rectifier inverters. These rectifier bridge units are connected in series or in parallel according to the requirements of each subsystem.

The basic rectifier unit is a 6-pulse bridge rated at 1 kV (no load), 20 kA (pulsed). The TF converter system consists of 36 rectifiers configured as four parallel strings of nine series-connected sections. This connection provides a 24-pulse dc output at up to 9 kV (no load) and 80 kA (pulsed). The EF system consists of 12 sections connected in series, generating a 24-pulse dc output at up to 12 kV (no load) and 20 kA (pulsed). The OH system consists of 18 sections connected, for most of the duty cycle, in series. This converter is a combination of 24-pulse and 12-pulse systems: up to 18 kV (no load) and 20 kA (pulsed). Any section can be bypassed by a special cyclic firing which supplies zero voltage but provides a path for the D.C. load current.

System Simulation

The complicated connection of all the dc bridges of the converter system for the TF, OH and EF systems, makes a full simulation complex. This study deals only with the harmonic content at the ac generator bus. Transferring the ac line current at the rectifier terminals to the generator bus permits parallel treatment of all the power supplies of the system.

a. The ac Line Current at Bridge Terminals in the Rectifying mode of Operation

The four rectifier bridges joining Figure 1's transformers, receive identical line-to-line rms voltages E_{LL} . They have the same commutating reactance X_c . Each bridge has its own firing delay angle α , but they share the same crest dc load current I_d .

The line current i_{21} in the transformer secondary, at the ac terminals of bridge 1, is shown in Figure 4. The equation of i_{21} for one-half cycle is:

$$\begin{aligned} i_{21} &= 0, \alpha \leq \omega t \leq \alpha + 30^\circ; \\ &= (E_m/(2X_c)) (\cos \alpha - \cos \omega t - 30^\circ), \\ &\quad \alpha + 30^\circ \leq \omega t \leq \alpha + u + 30^\circ; \\ &= I_d, \alpha + u + 30^\circ \leq \omega t \leq \alpha + 150^\circ; \\ &= I_d - (E_m/(2X_c)) (\cos \alpha - \cos (\omega t - 150^\circ)), \\ &\quad \alpha + 150^\circ \leq \omega t \leq \alpha + u + 150^\circ; \\ &= 0, \alpha + u + 150^\circ \leq \omega t \leq \alpha + 180^\circ; \end{aligned}$$

where u is the commutating angle and α is the firing delay angle. The other half-cycle is a mirror reflection of the above values. Each line current i_{21} , i_{22} , i_{23} , i_{14} , may have its own values of the various parameters.

b. The ac Line Current at Bridge Terminals in the Bypass mode of Operation

When a rectifier is bypassed using the cyclic firing mode, the ac line current at the terminal of the transformer secondary is as shown in Figure 6. The time frame in the simulation is modified because the cyclic firing frequency is one-fourth that of the 60 Hz (to 90 Hz) bridge firing. In other words, if the system's fundamental harmonic is at 60 Hz, the first subharmonic in the bypass mode is at 15 Hz.

c. Simulation of A Polygon/Delta/Wye Transformer

Figure 1 illustrates two polygon/delta/wye transformers with $+7.5^\circ$ phase difference between their primary voltages. This permits the generation of 24-pulse output where four bridges are connected in series (or parallel).

With a -7.5° Polygon/Delta/Wye transformer, the secondary voltage are respectively shifted by -37.5° and -7.5° relative to the primary voltage. For simulation purposes, it was assumed to be a Wye/Zig-Zag/Zig-Zag transformer with the same phase-shift (Figure 2).

With an assumption of 1:1 transformer ratio, the four coefficients are:

$$\left. \begin{aligned} A_1 &= \frac{\sin 22.5^\circ}{\sin 120^\circ} = 0.441584765 \\ A_2 &= \frac{\sin 37.5^\circ}{\sin 120^\circ} = 0.702937150 \end{aligned} \right\} \quad (1)$$

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$$\left. \begin{aligned} A_3 &= \frac{\sin 72.5^\circ}{\sin 120^\circ} = 0.916085529 \\ A_4 &= \frac{\sin 7.5^\circ}{\sin 120^\circ} = 0.150716604 \end{aligned} \right\} \quad (1)$$

The actual turns ratio is:

$$t = \frac{13.8}{0.7} = 19.7 \quad (2)$$

FIGURE 1
FOUR 3-PHASE BRIDGE CONNECTION
WITH TWO POLYGON TRANSFORMERS

FIGURE 2
SIMULATION OF 75° POLYGON DELTA/WYE
TRANSFORMER

FIGURE 3
SIMULATION OF +7.5° POLYGON DELTA/WYE
TRANSFORMER

Provided the line current in the transformer secondary is known, the primary line current reflected from the first secondary winding (-7.5 Polygon/Delta) is:

$$i_1 = i_{21} * A_1 * \frac{1}{t} \frac{1/-37.5^\circ}{1} + i_{21} * A_2 * \frac{1}{t} \frac{1/22.5^\circ}{1} \quad (3)$$

The primary line current reflected from the second secondary winding (+7.5 Polygon/Wye) is:

$$i_{11} = i_{22} * A_3 * \frac{1}{t} \frac{1/-3.5^\circ}{1} + i_{22} * A_4 * \frac{1}{t} \frac{1/28.5^\circ}{1} \quad (5)$$

Then, in Figure 1, $i_{a1} = i_1 + i_{11}$

With a +7.5° Polygon/Delta/Wye transformer, the secondary voltages are respectively shifted by +22.5° and +7.5° relative to the primary voltages. The simulated transformer is illustrated in Figure 2.

The primary line current reflected from the third secondary winding (+7.5° Polygon/Delta) is:

$$i_{111} = i_{23} * A_1 * \frac{1}{t} \frac{1/-22.5^\circ}{1} + i_{23} * A_2 * \frac{1}{t} \frac{1/37.5^\circ}{1} \quad (6)$$

The primary line current reflected from the fourth secondary winding (-7.5° Polygon/Wye) is:

$$i_{1V} = i_{24} * A_3 * \frac{1}{t} \frac{1/7.5^\circ}{1} + i_{24} * A_4 * \frac{1}{t} \frac{1/-32.5^\circ}{1} \quad (7)$$

Then in Figure 1, $i_{a2} = i_{111} + i_{1V}$

Then, $i_a = i_{a1} + i_{a2}$

FIGURE 4
AC LINE CURRENT THROUGH TRANSFORMER
SECONDARY

FIGURE 5
AC NETWORK ONE LINE DIAGRAM

FIGURE 6
AC LINE CURRENT THROUGH A TRANSFORMER
SECONDARY AT BYPASS MODE

4. The ac Network

A diagram of the ac network that feeds two transformers is illustrated in Figure 5. The reactances shown describe the generator, transformer, and current-limiting reactances. Transferring these reactances to the transformer secondary (20 MVA base),

$$X_G = 0.2 + \frac{20}{475} + 1.25 + \frac{20}{475} + 0.22 = 0.27 \text{ p.u.} \quad (10)$$

The line current in the generator consists of a combination of the currents of the power supply connections; therefore, the reactive voltage drop on its own reactance increases proportionally to the sum of simultaneous commutating currents. The actually used commutating reactance value was increased to

$$X_G = 0.3 \text{ p.u.} \quad (11)$$

Simulation Calculations

Calculations for this study were carried out by a computer program written in FORTRAN IV for the IBM 360/91 computer at Princeton University, utilizing a modified form of an existing Fourier analysis routine. Each current wave-form was analyzed for its complex Fourier coefficients separately modified by the angular shifts of equations (3) and (4), and multiplied by the coefficients of (1) and (2), and by appropriate integers for parallel power supplies.

Each harmonic current was multiplied by its frequency and the inductance to produce a set of Fourier voltage coefficients at the generator bus bar. These were synthesized into a voltage wave-form.

In addition, a combined wave-form was separately analyzed and the results compared for checking purposes.

RMS of Voltage and Current, TDF and PF

The resultant instantaneous current i , using Fourier waveform analysis, is given by:

$$i = \sum_n \{ A_n \cos \omega_n t + B_n \sin \omega_n t \} \quad (14)$$

rms value of the current is:

$$I_{rms} = \sqrt{\frac{1}{2} \sum_n \{ A_n^2 + B_n^2 \}} \quad (15)$$

where A_n, B_n = Fourier coefficients,

I_{rms} = RMS value of the current.

Assuming a sine wave for the generator no-load voltage (air-gap voltage), then the voltage at the bus bar is:

$$e_b = e_g - L_g \frac{di}{dt} = e_g \sin \omega_f t - L_g \sum_n \{ -\omega_n A_n \sin \omega_n t + \omega_n B_n \cos \omega_n t \} \quad (16)$$

where e_b = instantaneous voltage at the bus bar

e_g = generator voltage,

L_g = generator inductance,

ω_f = fundamental frequency

The RMS of the above voltage is:

$$E_{rms} = \sqrt{\frac{1}{2} \{ E_g^2 + L_g^2 \sum_n \omega_n^2 \{ A_n^2 + B_n^2 \} \}} \quad (17)$$

The Theoretical Deviation Factor (TDF) serves as an index of the degree of departure of the wave from an ideal sine shape; it is commonly used as a criterion for adequacy of ac filters. This value is computed according to:

$$TDF = \left(\sum_{n=1}^{\infty} \frac{I_n}{I_f} \right) / I_f$$

where: I_f = Crest value of the Fundamental,

I_n = Crest value of harmonic n ,

n = Total number of harmonics computed.

The power-factor (PF) is calculated by:

$$PF = \frac{V_{in} \cdot I_f \cdot \cos \phi_f}{V_{in} \cdot I_{rms}} \quad (17)$$

where: V_{in} = Generator voltage at no-load,

I_{rms} = RMS value of the line current,

I_f = RMS value of the fundamental,

where: $\cos \phi_f$ = Power factor of the fundamental

Telephone Interference Study

It was assumed that a telephone line is located within 3 m of a power line to one transformer. The length of exposure is about 50 m. The criterion is

$$V_w = E \sqrt{\frac{1}{n} \{ I_{rn}^2 + L_n^2 + K_{sn}^2 + K_{bn}^2 + P_n \}} \quad (18)$$

where:

V_w = Phrophometric voltage (Transferance Noise Voltage)

E = Length of exposure (meter)

I_r = Residual current of harmonic order n is power line (a)

Z_n = Mutual impedance between power line and telephone line = $\omega_n \times M$

K_{sn} = Screening factor (assumed unity)

K_{bn} = Balance factor (assumed unity)

P_n = Phrophometric weighting (Table in Kimbark)

The maximum recommended V_w is 1 mV (6).

Due to the overhead lines (there are no ground return lines), the mutual inductance is:

$$M = (\mu_0 / 2\pi) \ln (b/a) \quad (19)$$

where b & a are distances to the farther and nearer telecommunication lines, resulting in

$$M = 6.56 \times 10^{-9} \text{ Henry,}$$

$$\text{if } b = 3.1 \text{ meters and } a = 3.0 \text{ meters}$$

If two converters, (out of the four connected to the same transformer,) are bypassed, and the other two

are phase controlled with delay angle of 50° , and dc load current is 20 kA, then the result is:

$$V_{\text{TH}} = 54.8 \text{ mV,}$$

which is much larger than the recommended 1 mV.

Analysis Case

The current and voltage distortion are described in reference (11). Six extremes were chosen for the analysis, of which one is described in Table I.

Table I: Operating Conditions for Sample Case

No. of Pulses	Total Peak Current (KA)	Power MW	$\frac{a}{\omega}$ deg/Pulse	No. of Pulses
TE	20	92.5	100	0
COILS	4	18.5	77	20
15.05KV	12	55.5 (Bypassed*)		
EF Coils	8	34	40	00
36.9KV	2	7	10	90
	2	2 (Bypassed*)		
OH Coils	16	12	80	0
4.18KV	2	8	20	0

*Bypassed Sections (2) (3)

This information was provided to the computer simulation to calculate RMS voltage and current at the main bus bar, the % to power factor, and theoretical deviation factor of the waveforms. The frequency used was 63 Hz, which is the value expected by the time flat-top is reached. The harmonic content for those larger than 1% was found to be as shown in Table II.

Table II: Harmonics at Bus Bar (Sample Case)

Harmonic # (1.575 Hz)	1	2	4	5	7	8	10	12	100	150	160
Harmonic # (1 Hz)	1/4	1/2	1	1-1/4	1-3/4	2	2-1/2	2 1/2	25	42	44
Current %	3.6	3.3	100	2.7	2.2	1.7	1.6	*	*	*	*
Voltage %	*	*	100	*	*	*	*	*	2.0	1.9	1.1

*These and all others were less than 1%.

Additional results were:

Line current (rms)	37.13 KA
Current TDF	15.1 %
Phase voltage (rms)	7.96 KV
Voltage TDF	6.3 %
Power Factor	0.842 lagging

(The TDF values are related to the fundamental harmonic line current of 37.05 KA (rms) and phase voltage 7.96 KV (rms).

As shown in Table II, the major deviation of the current from a pure sine wave is caused by the low-frequency harmonics (1/4 - 2-1/2 times the 63 Hz

fundamental), with the fractional multiples (subharmonics) caused by the bypass mode operations. The major deviation of the voltage from a pure sine wave is caused by the characteristic harmonics of the rectifiers (10, 20, 40, 80, 160). The low-frequency voltage harmonics are relatively smaller because of the low impedance at these frequencies. The wave shapes for the current and voltage of Table II are shown in Figures 1 and 2, respectively.

Concluding Remarks

This paper describes methods not only to reduce harmonic content in the main bus bar voltage and current. Each power supply section, out of which was generated separately in order to analyze the total generated waveforms, with respect to the effect of the delayed firing angle on the harmonic content of the system (as related to the commutating inductance of the system). The results show the advantage of the current and voltage at the generator terminals when the fully loaded. It also calculates the theoretical Deviation Factor of each current and voltage (sine wave), and the Power Factor of the total system.

The distortion of the TE waveform is caused mainly by the low-frequency subharmonics generated by the bypassed bridge rectifiers. There is no danger of overheating the generator transformers or capacitors because of the low frequencies.

A very distorted current waveform may cause stability problems, especially during the transient control of the converter (the firing condition).

The characteristic harmonics (10, 20, 40, 80, 160) of the current waveform is produced by the bypass within the generator requirements (reference 11).

special filter is needed. These harmonics produce the distortion of the voltage waveform at the main bus bar and depend on the voltage drop across the generator reactance.

The results also show relatively high noise voltage (psophometric voltage) on a telephone line. This voltage is generated by the residual harmonic currents; therefore, it is advised that shielded telecommunication lines be used.

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FIG 7

FIG. 8