Brushless self-excited single-phase synchronous generator
Part II - Improved rotor excitation technique

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The brushless self-excited single-phase synchronous generator is a three-phase induction machine where the stator constitute the excitation winding and load winding, while the rotor windings are connected through diodes to rectify double frequency induced voltages. A rotor diodes configuration using three-diodes is suggested for improved output voltage waveform. The effect of changing machine parameters is also investigated. The generator operates synchronously to produce output voltage where residual magnetism is needed for self-excitation. This paper presents theoretical investigation for transient and steady-state performance based on voltage equations in real machine variables. The study revealed that using three-diodes improves to a large extent the harmonic content of the output voltage waveform. The study, also showed that the machine parameters have some effect on harmonic content.

يعتمذ هذا البحث علي تمثيل آلة حثيه ثلاثية الأوجه بمجموعة من الملفات ترتبط معا مغناطيسيا لتوليد الجهد حيث تم توصيل العضو الدوار من خلال مقومات وذلك لتقويم الجهد ذات التردد المضاعف لتوليد تيار الاثارة. في هذا البحث تم اقتراح طريقة تستخدم ثلاثة مقومات في العضو الدوار وذلك بغرض تحسين جهد الخرج. ويقدم البحث تحليل للآلة يستخدم في دراسة خواص الآلة في الحالة العابرة وحالة الاستقرار عند اللاحمل أو الحمل . وقد بينت الدراسة أن الطريقة الجديدة لتوصيل المقومات قد حسنت بشكل كبير جدا التحليل الطيفي لجهد الخرج. كذلك أظهرت الدراسة أن تغيير باراميترات الآلة له بعض التأثير علي التحليل الطيفي لجهد الخرج.

Keywords: Induction machine, Brushless self-excited, Synchronous generator

1. Introduction

A large number of attempts have been made by some authors in the development of the Brushless Self-Excited Single-Phase Synchronous Generator (BSESPSG) [1-5]. This is due to its various advantages over conventional synchronous generator such as simplicity in structure, no separate dc source for excitation and above all least maintenance. Ref. [1] proposed a three-phase motor of slip-ring type to replace ref.[2] system as shown in fig. 1. Part I [6] was the scope for investigating the effect of using either one or two diodes on the rotor circuit. This paper is concerned with an attempt to improve the output voltage waveform. For this reason a rotor diode configuration is proposed where three diodes are used instead of two diodes. Fig. 2 shows this proposed diode configuration.

As the machine runs, and using the residual magnetism present in the rotor body, a small amount of induced voltage will be produced circulating current in stator capacitor winding. A pulsating field will then result in the air gap due to the circulating current in the excitation winding. The pulsating flux can be resolved into two rotating flux components. The backward component of flux will move opposite to rotor rotation and hence induces double frequency voltage in the rotor circuit. Rectifying this voltage produces a dc rotor field excitation which will contribute to increased stator induced voltage. Consequently the voltage induced in the rotor windings will grow up giving rise to more circulating current. The procedure will continue until balance is reached by virtue of saturation and self excitation is achieved in this case.

The voltage equations in machine variables given in part I are used here for the simulation purposes. Also, saturation effect equations given in part I [6] is going to be used.

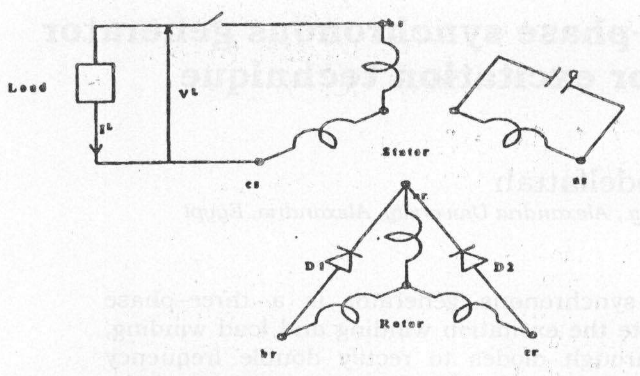


Fig. 1. Construction of BSESPSG using two diodes.

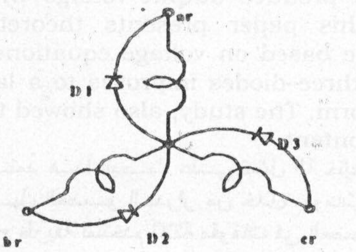


Fig. 2. Proposed rotor diode configuration.

2. Proposed diode configuration

The proposed generator is analysed using voltage equations in machine variables mentioned in part I [6] under different diode connections. As has been mentioned earlier, one of the stator phases is connected across a capacitor to perform as the excitation winding , and the output voltage will be the phase resultant of the remaining two phases as shown in fig. 1.

2.1. Excitation winding

$$V_c = -V_{as} = (1/C) \int i_{as}\, dt = Q/C, \tag{1}$$

Where,

$$Q = \int i_{as}\, dt \qquad \text{i.e.} \qquad pQ = i_{as}. \tag{2}$$

Substituting eq. (1) of part I [6] into eq. (1) we get:

$$L_s\, p i_{as} = -r_s i_{as} - Q/C - L_{sr}\, p[\, i_{ar} \cos\theta + i_{br} \cos\phi_1 + i_{cr} \cos\phi_2]. \tag{3}$$

2.2. No-load analysis

Output winding

At no-load $i_{bs} = i_{cs} = 0$,

$$\begin{aligned} V_{NL} &= V_{bs} - V_{cs} \\ &= \sqrt{3}\, L_{sr}[\cos\phi_6\, p i_{ar} + \cos\phi_4\, p i_{br} + \cos\phi_7\, p i_{cr}] - \sqrt{3}\, L_{sr}\omega[\sin\phi_6\, i_{ar} + \sin\phi_4\, i_{br} + \sin\phi_7\, i_{cr}]. \end{aligned} \tag{4}$$

Rotor windings

Eight states are possible. Using machine equations given in part I [6] and eqs. [1-4] we get the following states.

-Diodes D1–OFF , D2– OFF & D3–OFF

$i_{ar} = i_{br} = i_{cr} = 0$,
$i_{D1} = 0$, $i_{D2} = 0$ & $i_{D3} = 0$

$$\begin{bmatrix} p i_{as} \\ pQ \end{bmatrix} = \begin{bmatrix} L_s & 0 \\ 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} -r_s & -1/C \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_{as} \\ Q \end{bmatrix}, \tag{5}$$

$$\begin{aligned} V_{D1} &= -V_{ar} \\ &= -L_{sr}[\cos\theta\, p i_{as} - \omega \sin\theta\, i_{as}], \end{aligned} \tag{6}$$

$$\begin{aligned} V_{D2} &= V_{br} \\ &= L_{sr}[\cos\phi_1\, p i_{as} - \omega \sin\phi_1\, i_{as}], \end{aligned} \tag{7}$$

$$\begin{aligned} V_{D3} &= V_{cr} \\ &= L_{sr}[\cos\phi_2\, p i_{as} - \omega \sin\phi_2\, i_{as}]. \end{aligned} \tag{8}$$

-Diode D1–ON , D2–OFF & D3–OFF

$i_{D1} = i_{ar}$, $i_{D2} = 0$ & $i_{D3} = 0$,
$i_{br} = 0$ & $i_{cr} = 0$
$V_{D1} = -V_{ar} = 0$,

$$\begin{bmatrix} p i_{as} \\ p i_{ar} \\ pQ \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\theta & 0 \\ L_{sr}\cos\theta & L_r & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \times \begin{bmatrix} -r_s & L_{sr}\omega\sin\theta & -1/C \\ L_{sr}\omega\sin\theta & -r_r & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{ar} \\ Q \end{bmatrix}, \tag{9}$$

$$\begin{aligned} V_{D2} &= V_{br} \\ &= -(^1/_2)\, L_{mr}\, p i_{ar} + L_{sr}[\cos\phi_1\, p i_{as} - \omega \sin\phi_1\, i_{as}], \end{aligned} \tag{10}$$

$$
\begin{aligned}
V_{D3} &= V_{cr} \\
&= -(^1/_2)\, L_{mr}\, pi_{ar} \\
&\quad + L_{sr}\, [\, \cos\phi_2\, pi_{as} - \omega \sin\phi_2\, i_{as}\,]. \qquad (11)
\end{aligned}
$$

-Diode D1–OFF , D2–ON & D3–OFF

$i_{D1}=0$, $i_{D2} = -i_{br}$ and $i_{D3} = 0$,
$i_{ar} = 0$ & $i_{cr} = 0$,
$V_{D2} = V_{br} = 0$.

$$
\begin{bmatrix} pi_{as} \\ pi_{br} \\ pQ \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\phi_1 & 0 \\ L_{sr}\cos\phi_1 & L_r & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \times
\begin{bmatrix} -r_s & L_{sr}\omega\sin\phi_1 & -1/C \\ L_{sr}\omega\sin\phi_1 & -r_r & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{br} \\ Q \end{bmatrix}, \qquad (12)
$$

$$
\begin{aligned}
V_{D1} &= -V_{ar} \\
&= (^1/_2)\, L_{mr}\, pi_{br} \\
&\quad - L_{sr}\, [\, \cos\theta\, pi_{as} - \omega \sin\theta\, i_{as}\,], \qquad (13)
\end{aligned}
$$

$$
\begin{aligned}
V_{D3} &= V_{cr} \\
&= -(^1/_2)\, L_{mr}\, pi_{br} \\
&\quad + L_{sr}\, [\, \cos\phi_2\, pi_{as} - \omega \sin\phi_2\, i_{as}\,]. \qquad (14)
\end{aligned}
$$

-Diode D1–OFF , D2–OFF & D3–ON

$i_{D1} = 0$, $i_{D2} = 0$ & $i_{D3} = -i_{cr}$,
$i_{ar} = 0$ & $i_{br} = 0$,
$V_{D3} = V_{cr} = 0$.

$$
\begin{bmatrix} pi_{as} \\ pi_{cr} \\ pQ \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\phi_2 & 0 \\ L_{sr}\cos\phi_2 & L_r & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \times
\begin{bmatrix} -r_s & L_{sr}\omega\sin\phi_2 & -1/C \\ L_{sr}\omega\sin\phi_2 & -r_r & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{cr} \\ Q \end{bmatrix}, \qquad (15)
$$

$$
\begin{aligned}
V_{D1} &= -V_{ar} \\
&= (^1/_2)\, L_{mr}\, pi_{cr} \\
&\quad - L_{sr}\, [\, \cos\theta\, pi_{as} - \omega \sin\theta\, i_{as}\,], \qquad (16)
\end{aligned}
$$

$$
\begin{aligned}
V_{D2} &= V_{br} \\
&= -(^1/_2)\, L_{mr}\, pi_{cr} \\
&\quad + L_{sr}\, [\, \cos\phi_1\, pi_{as} - \omega \sin\phi_1\, i_{as}\,]. \qquad (17)
\end{aligned}
$$

-Diode D1–ON , D2–ON & D3–OFF

$i_{D1} = i_{ar}$, $i_{D2} = -i_{br}$ & $i_{D3} = 0$,
$i_{cr} = 0$,
$V_{D1} = -V_{ar} = 0$,
$V_{D2} = V_{br} = 0$,

$$
\begin{bmatrix} pi_{as} \\ pi_{ar} \\ pi_{br} \\ pQ \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\theta & L_{sr}\cos\phi_1 & 0 \\ L_{sr}\cos\theta & L_r & -(1/2)L_{mr} & 0 \\ L_{sr}\cos\phi_1 & -(1/2)L_{mr} & L_r & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^{-1} \times
\begin{bmatrix} -r_s & L_{sr}\omega\sin\theta & L_{sr}\omega\sin\phi_1 & -1/C \\ L_{sr}\omega\sin\theta & -r_r & 0 & 0 \\ L_{sr}\omega\sin\phi_1 & 0 & -r_r & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{ar} \\ i_{br} \\ Q \end{bmatrix} \qquad (18)
$$

$$
\begin{aligned}
V_{D3} &= V_{cr} \\
&= -(^1/_2)\, L_{mr}\, pi_{ar} - (^1/_2)\, L_{mr}\, pi_{br} \\
&\quad + L_{sr}\, [\, \cos\phi_2\, pi_{as} - \omega \sin\phi_2\, i_{as}\,]. \qquad (19)
\end{aligned}
$$

-Diode D1–OFF , D2–ON & D3–ON

$i_{D1} = 0$, $i_{D2} = -i_{br}$ & $i_{D3} = -i_{cr}$,
$i_{ar} = 0$,
$V_{D2} = V_{br} = 0$ & $V_{D3} = V_{cr} = 0$,

$$
\begin{bmatrix} pi_{as} \\ pi_{br} \\ pi_{cr} \\ pQ \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\phi_1 & L_{sr}\cos\phi_2 & 0 \\ L_{sr}\cos\phi_1 & L_r & -(1/2)L_{mr} & 0 \\ L_{sr}\cos\phi_2 & -(1/2)L_{mr} & L_r & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^{-1} \times
\begin{bmatrix} -r_s & L_{sr}\omega\sin\phi_1 & L_{sr}\omega\sin\phi_2 & -1/C \\ L_{sr}\omega\sin\phi_1 & -r_r & 0 & 0 \\ L_{sr}\omega\sin\phi_2 & 0 & -r_r & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{br} \\ i_{cr} \\ Q \end{bmatrix} \qquad (20)
$$

$$
\begin{aligned}
V_{D1} &= -V_{ar} \\
&= (^1/_2)\, L_{mr}\, pi_{br} + (^1/_2)\, L_{mr}\, pi_{cr} \\
&\quad - L_{sr}\, [\, \cos\theta\, pi_{as} - \omega \sin\theta\, i_{as}\,]. \qquad (21)
\end{aligned}
$$

-Diode D1–ON , D2–OFF & D3–ON

$i_{D1} = i_{ar}$, $i_{D2} = 0$ & $i_{D3} = -i_{cr}$,
$i_{br} = 0$,
$V_{D1} = -V_{ar} = 0$ & $V_{D3} = V_{cr} = 0$,

$$\begin{bmatrix} pi_{as} \\ pi_{ar} \\ pi_{cr} \\ pQ \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\theta & L_{sr}\cos\phi_2 & 0 \\ L_{sr}\cos\theta & L_r & -(1/2)L_{mr} & 0 \\ L_{sr}\cos\phi_2 & -(1/2)L_{mr} & L_r & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^{-1} \times \begin{bmatrix} -r_s & L_{sr}\omega\sin\theta & L_{sr}\omega\sin\phi_2 & -1/C \\ L_{sr}\omega\sin\theta & -r_r & 0 & 0 \\ L_{sr}\omega\sin\phi_2 & 0 & -r_r & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{ar} \\ i_{br} \\ Q \end{bmatrix} \tag{22}$$

$$V_{D2} = V_{br}$$
$$= -(^1/_2)\, L_{mr}\, pi_{ar} - (^1/_2)\, L_{mr}\, pi_{cr} + L_{sr}\, [\,\cos\phi_1\, pi_{as} - \omega\sin\phi_1\, i_{as}\,]. \tag{23}$$

-Diode D1–ON , D2–ON & D3–ON

$i_{D1} = i_{ar}$, $i_{D2} = -i_{br}$ & $i_{D3} = -i_{cr}$,
$V_{D1} = -V_{ar} = 0$, $V_{D2} = V_{br} = 0$ & $V_{D3} = V_{cr} = 0$.

$$\begin{bmatrix} pi_{as} \\ pi_{ar} \\ pi_{br} \\ pi_{cr} \\ pQ \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\theta & L_{sr}\cos\phi_1 & L_{sr}\cos\phi_2 & 0 \\ L_{sr}\cos\theta & L_r & -(1/2)L_{mr} & -(1/2)L_{mr} & 0 \\ L_{sr}\cos\phi_1 & -(1/2)L_{mr} & L_r & -(1/2)L_{mr} & 0 \\ L_{sr}\cos\phi_2 & -(1/2)L_{mr} & -(1/2)L_{mr} & L_r & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{-1} \times \begin{bmatrix} r_s & L_{sr}\omega\sin\theta & L_{sr}\omega\sin\phi_1 & L_{sr}\omega\sin\phi_2 & -1/C \\ L_{sr}\omega\sin\theta & -r_r & 0 & 0 & 0 \\ L_{sr}\omega\sin\phi_1 & 0 & -r_r & & 0 \\ L_{sr}\omega\sin\phi_2 & 0 & 0 & -r_r & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{ar} \\ i_{br} \\ i_{cr} \\ Q \end{bmatrix}, \tag{24}$$

2.3. Load analysis

Output winding

With load $I_L = i_{cs} = -\, i_{bs}$

$$V_L = V_{bs} - V_{cs}$$
$$= 2\, r_s\, i_{bs} + 2\, L_{ss}\, pi_{bs} + \sqrt{3}\, L_{sr}[\,\cos\phi_6\, pi_{ar} + \cos\phi_4\, pi_{br} + \cos\phi_7\, pi_{cr}] - \sqrt{3}\, L_{sr}\omega[\,\sin\phi_6\, i_{ar} + \sin\phi_4\, i_{br} + \sin\phi_7\, i_{cr}], \tag{25}$$

$$= -\, R_L\, i_{bs} - L_L\, pi_{bs}\,, \tag{26}$$

where $L_{ss} = L_s + (^1/_2)\, L_{ms}$.

Rotor windings

-Diodes D1–OFF , D2– OFF & D3–OFF

$i_{ar} = i_{br} = i_{cr} = 0$,
$i_{D1} = 0$, $i_{D2} = 0$ & $i_{D3} = 0$,

$$\begin{bmatrix} pi_{as} \\ pQ \\ pi_{bs} \end{bmatrix} = \begin{bmatrix} L_s & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2L_{ss}+L_L \end{bmatrix}^{-1} \begin{bmatrix} -r_s & -1/C & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -(2r_s+R_L) \end{bmatrix} \begin{bmatrix} i_{as} \\ Q \\ i_{bs} \end{bmatrix}, \tag{27}$$

$$V_{D1} = -V_{ar}$$
$$= -L_{sr}\,[\,\cos\theta\, pi_{as} - \omega\sin\theta\, i_{as}\,] - \sqrt{3}\, L_{sr}\,[\,\cos\phi_6\, pi_{bs} - \omega\sin\phi_6\, i_{bs}\,]. \tag{28}$$

$$V_{D2} = V_{br}$$
$$= L_{sr}\,[\,\cos\phi_1\, pi_{as} - \omega\sin\phi_1\, i_{as}\,] + \sqrt{3}\, L_{sr}\,[\,\cos\phi_4\, pi_{bs} - \omega\sin\phi_4\, i_{bs}\,], \tag{29}$$

$$V_{D3} = V_{cr}$$
$$= L_{sr}\,[\,\cos\phi_2\, pi_{as} - \omega\sin\phi_2\, i_{as}\,] + \sqrt{3}\, L_{sr}\,[\,\cos\phi_7\, pi_{bs} - \omega\sin\phi_7\, i_{bs}\,], \tag{30}$$

-Diode D1–ON , D2–OFF & D3–OFF

$i_{D1} = i_{ar}$, $i_{D2} = 0$ & $i_{D3} = 0$,
$i_{br} = 0$ & $i_{cr} = 0$,
$V_{D1} = -V_{ar} = 0$,

$$\begin{bmatrix} p\,i_{as} \\ p\,i_{ar} \\ pQ \\ p\,i_{bs} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\theta & 0 & 0 \\ L_{sr}\cos\theta & L_r & 0 & \sqrt{3}L_{sr}\cos\phi_6 \\ 0 & 0 & 1 & 0 \\ 0 & \sqrt{3}L_{sr}\cos\phi_6 & 0 & 2L_{ss}+L_L \end{bmatrix}^{-1} \times$$

$$\begin{bmatrix} -r_s & L_{sr}\omega\sin\theta & -1/C & 0 \\ L_{sr}\omega\sin\theta & -r_r & 0 & \sqrt{3}\,L_{sr}\omega\sin\phi_6 \\ 1 & 0 & 0 & 0 \\ 0 & \sqrt{3}\,L_{sr}\omega\sin\phi_6 & 0 & -(2r_s+R_L) \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{ar} \\ Q \\ i_{bs} \end{bmatrix}, \tag{31}$$

$$\begin{aligned} V_{D2} &= V_{br} \\ &= -(^1/_2)\, L_{mr}\, pi_{ar} + L_{sr}\,[\cos\phi_1\, pi_{as} \\ &\quad - \omega\sin\phi_1\, i_{as}\,] + \sqrt{}\,3L_{sr}\,[\,\cos\phi_4\, pi_{bs} \\ &\quad - \omega\sin\phi_4\, i_{bs}\,], \end{aligned} \tag{32}$$

$$\begin{aligned} V_{D3} &= V_{cr} \\ &= -(^1/_2)\, L_{mr}\, pi_{ar} + L_{sr}\,[\,\cos\phi_2\, pi_{as} \\ &\quad - \omega\sin\phi_2\, i_{as}\,] + \sqrt{}\,3\, L_{sr}\,[\,\cos\phi_7\, pi_{bs} \\ &\quad - \omega\sin\phi_7\, i_{bs}\,]. \end{aligned} \tag{33}$$

-Diode D1–OFF , D2–ON & D3–OFF

$i_{D1} = 0 \quad , \quad i_{D2} = -i_{br} \;\;\&\;\; i_{D3} = 0,$
$i_{ar} = 0 \;\;\&\;\; i_{cr} = 0,$
$V_{D2} = V_{br} = 0,$

$$\begin{bmatrix} p\,i_{as} \\ p\,i_{br} \\ pQ \\ p\,i_{bs} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\phi_1 & 0 & 0 \\ L_{sr}\cos\phi_1 & L_r & 0 & \sqrt{3}L_{sr}\cos\phi_4 \\ 0 & 0 & 1 & 0 \\ 0 & \sqrt{3}L_{sr}\cos\phi_4 & 0 & 2L_{ss}+L_L \end{bmatrix}^{-1} \times$$

$$\begin{bmatrix} -r_s & L_{sr}\omega\sin\phi_1 & -1/C & 0 \\ L_{sr}\omega\sin\phi_1 & -r_r & 0 & \sqrt{3}\,L_{sr}\omega\sin\phi_4 \\ 1 & 0 & 0 & 0 \\ 0 & \sqrt{3}\,L_{sr}\omega\sin\phi_4 & 0 & -(2r_s+R_L) \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{br} \\ Q \\ i_{bs} \end{bmatrix}, \tag{34}$$

$$\begin{aligned} V_{D1} &= -V_{ar} \\ &= (^1/_2)\, L_{mr}\, pi_{br} - L_{sr}\,[\,\cos\theta\, pi_{as} \\ &\quad - \omega\sin\theta\, i_{as}\,] - \sqrt{}\,3\, L_{sr}\,[\,\cos\phi_6\, pi_{bs} \\ &\quad - \omega\sin\phi_6\, i_{bs}\,], \end{aligned} \tag{35}$$

$$\begin{aligned} V_{D3} &= V_{cr} \\ &= -(^1/_2)\, L_{mr}\, pi_{br} + L_{sr}\,[\,\cos\phi_2\, pi_{as} \\ &\quad - \omega\sin\phi_2\, i_{as}\,] + \sqrt{}\,3\, L_{sr}\,[\,\cos\phi_7\, pi_{bs} \\ &\quad - \omega\sin\phi_7\, i_{bs}\,]. \end{aligned} \tag{36}$$

- Diode D1–OFF , D2–OFF & D3–ON

$i_{D1} = 0 \quad , \quad i_{D2} = 0 \;\;\&\;\; i_{D3} = -i_{cr},$
$i_{ar} = 0 \;\;\&\;\; i_{br} = 0,$
$V_{D3} = V_{cr} = 0,$

$$\begin{bmatrix} p\, i_{as} \\ p\, i_{cr} \\ pQ \\ p\, i_{bs} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\phi_2 & 0 & 0 \\ L_{sr}\cos\phi_2 & L_r & 0 & \sqrt{3}L_{sr}\cos\phi_7 \\ 0 & 0 & 1 & 0 \\ 0 & \sqrt{3}L_{sr}\cos\phi_7 & 0 & 2L_{ss}+L_L \end{bmatrix}^{-1} \times \begin{bmatrix} -r_s & L_{sr}\,\omega\sin\phi_2 & -1/C & 0 \\ L_{sr}\,\omega\sin\phi_2 & -r_r & 0 & \sqrt{3}L_{sr}\,\omega\sin\phi_7 \\ 1 & 0 & 0 & 0 \\ 0 & \sqrt{3}L_{sr}\,\omega\sin\phi_7 & 0 & -(2r_s+R_L) \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{cr} \\ Q \\ i_{bs} \end{bmatrix}, \tag{37}$$

$$\begin{aligned} V_{D1} &= -V_{ar} \\ &= (^1/_2)\, L_{mr}\, pi_{cr} - L_{sr}\, [\, \cos\theta\, pi_{as} \\ &\quad - \omega\sin\theta\, i_{as}\,] - \sqrt{3}\, L_{sr}\, [\, \cos\phi_6\, pi_{bs} \\ &\quad - \omega\sin\phi_6\, i_{bs}\,], \end{aligned} \tag{38}$$

$$\begin{aligned} V_{D2} &= V_{br} \\ &= -(^1/_2)\, L_{mr}\, pi_{cr} + L_{sr}\, [\, \cos\phi_1\, pi_{as} \\ &\quad -\omega\sin\phi_1 i_{as}\,] + \sqrt{3}\, L_{sr}\, [\, \cos\phi_4\, pi_{bs} \\ &\quad - \omega\sin\phi_4\, i_{bs}\,]. \end{aligned} \tag{39}$$

-Diode D1–ON , D2–ON & D3–OFF

$i_{D1} = i_{ar}$, $i_{D2} = -i_{br}$ & $i_{D3} = 0$,
$i_{cr} = 0$,
$V_{D1} = -V_{ar} = 0$ & $V_{D2} = V_{br} = 0$,

$$\begin{bmatrix} p\, i_{as} \\ p\, i_{ar} \\ p\, i_{br} \\ pQ \\ p\, i_{bs} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\theta & L_{sr}\cos\phi_1 & 0 & 0 \\ L_{sr}\cos\theta & L_r & -(1/2)L_{mr} & 0 & \sqrt{3}L_{sr}\cos\phi_6 \\ L_{sr}\cos\phi_1 & -(1/2)L_{mr} & L_r & 0 & \sqrt{3}L_{sr}\cos\phi_4 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & \sqrt{3}L_{sr}\cos\phi_6 & \sqrt{3}L_{sr}\cos\phi_4 & 0 & 2L_{ss}+L_L \end{bmatrix}^{-1} \times \begin{bmatrix} -r_s & L_{sr}\,\omega\sin\theta & L_{sr}\,\omega\sin\phi_1 & -1/C & 0 \\ L_{sr}\,\omega\sin\theta & -r_r & 0 & 0 & \sqrt{3}L_{sr}\,\omega\sin\phi_6 \\ L_{sr}\,\omega\sin\phi_1 & 0 & -r_r & 0 & \sqrt{3}L_{sr}\,\omega\sin\phi_4 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & \sqrt{3}L_{sr}\,\omega\sin\phi_6 & \sqrt{3}L_{sr}\,\omega\sin\phi_4 & 0 & -(2r_s+R_L) \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{ar} \\ i_{br} \\ Q \\ i_{bs} \end{bmatrix}, \tag{40}$$

$$\begin{aligned} V_{D3} &= V_{cr} \\ &= -(^1/_2)\, L_{mr}\, pi_{ar} -(^1/_2)\, L_{mr}\, pi_{br} \\ &\quad + L_{sr}\, [\, \cos\phi_2\, pi_{as} - \omega\sin\phi_2\, i_{as}\,] \\ &\quad + \sqrt{3}\, L_{sr}\, [\, \cos\phi_7\, pi_{bs} - \omega\sin\phi_7\, i_{bs}\,]. \end{aligned} \tag{41}$$

- Diode D1–OFF , D2–ON & D3–ON

$i_{D1} = 0$, $i_{D2} = -i_{br}$ & $i_{D3} = -i_{cr}$,
$i_{ar} = 0$,
$V_{D2} = V_{br} = 0$ & $V_{D3} = V_{cr} = 0$,

$$\begin{bmatrix} pi_{as} \\ pi_{br} \\ pi_{cr} \\ pQ \\ pi_{bs} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\phi_1 & L_{sr}\cos\phi_2 & 0 & 0 \\ L_{sr}\cos\phi_1 & L_r & -(1/2)L_{mr} & 0 & \sqrt{3}L_{sr}\cos\phi_4 \\ L_{sr}\cos\phi_2 & -(1/2)L_{mr} & L_r & 0 & \sqrt{3}L_{sr}\cos\phi_7 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & \sqrt{3}L_{sr}\cos\phi_4 & \sqrt{3}L_{sr}\cos\phi_7 & 0 & 2L_{ss}+L_L \end{bmatrix}^{-1} \times$$

$$\begin{bmatrix} -r_s & L_{sr}\omega\sin\phi_1 & L_{sr}\omega\sin\phi_2 & -1/C & 0 \\ L_{sr}\omega\sin\phi_1 & -r_r & 0 & 0 & \sqrt{3}\,L_{sr}\omega\sin\phi_4 \\ L_{sr}\omega\sin\phi_2 & 0 & -r_r & 0 & \sqrt{3}\,L_{sr}\omega\sin\phi_7 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & \sqrt{3}\,L_{sr}\omega\sin\phi_4 & \sqrt{3}\,L_{sr}\omega\sin\phi_7 & 0 & -(2r_s+R_L) \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{br} \\ i_{cr} \\ Q \\ i_{bs} \end{bmatrix}, \tag{42}$$

$$\begin{aligned} V_{D1} &= -V_{ar} \\ &= (^1/_2)\,L_{mr}\,pi_{br} + (^1/_2)\,L_{mr}\,pi_{cr} \\ &\quad - L_{sr}\,[\,\cos\theta\,pi_{as} - \omega\sin\theta\,i_{as}\,] \\ &\quad -\sqrt{3}\,L_{sr}\,[\,\cos\phi_6\,pi_{bs} - \omega\sin\phi_6\,i_{bs}]. \end{aligned} \tag{43}$$

-Diode D1–ON , D2–OFF & D3–ON

$i_{D1} = i_{ar}$, $i_{D2} = 0$ & $i_{D3} = -i_{cr}$,
$i_{br} = 0$,
$V_{D1} = -V_{ar} = 0$ & $V_{D3} = V_{cr} = 0$,

$$\begin{bmatrix} pi_{as} \\ pi_{ar} \\ pi_{cr} \\ pQ \\ pi_{bs} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\theta & L_{sr}\cos\phi_2 & 0 & 0 \\ L_{sr}\cos\theta & L_r & -(1/2)L_{mr} & 0 & \sqrt{3}L_{sr}\cos\phi_6 \\ L_{sr}\cos\phi_2 & -(1/2)L_{mr} & L_r & 0 & \sqrt{3}L_{sr}\cos\phi_7 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & \sqrt{3}L_{sr}\cos\phi_6 & \sqrt{3}L_{sr}\cos\phi_7 & 0 & 2L_{ss}+L_L \end{bmatrix}^{-1} \times$$

$$\begin{bmatrix} -r_s & L_{sr}\omega\sin\theta & L_{sr}\omega\sin\phi_2 & -1/C & 0 \\ L_{sr}\omega\sin\theta & -r_r & 0 & 0 & \sqrt{3}\,L_{sr}\omega\sin\phi_6 \\ L_{sr}\omega\sin\phi_2 & 0 & -r_r & 0 & \sqrt{3}\,L_{sr}\omega\sin\phi_7 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & \sqrt{3}\,L_{sr}\omega\sin\phi_6 & \sqrt{3}\,L_{sr}\omega\sin\phi_7 & 0 & -(2r_s+R_L) \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{ar} \\ i_{cr} \\ Q \\ i_{bs} \end{bmatrix}, \tag{44}$$

$$\begin{aligned} V_{D2} &= V_{br} \\ &= -(^1/_2)\,L_{mr}\,pi_{ar} - (^1/_2)\,L_{mr}\,pi_{cr} \\ &\quad + L_{sr}\,[\,\cos\phi_1\,pi_{as} - \omega\sin\phi_1\,i_{as}\,] \\ &\quad + \sqrt{3}\,L_{sr}[\cos\phi_4 pi_{bs} - \omega\sin\phi_4\,i_{bs}]. \end{aligned} \tag{45}$$

- Diode D1–ON , D2–ON & D3–ON

$i_{D1} = i_{ar}$, $i_{D2} = -i_{br}$ & $i_{D3} = -i_{cr}$
$V_{D1} = -V_{ar} = 0$, $V_{D2} = V_{br} = 0$ & $V_{D3} = V_{cr} = 0$,

$$\begin{bmatrix} p\,i_{as} \\ p\,i_{ar} \\ p\,i_{br} \\ p\,i_{cr} \\ pQ \\ p\,i_{bs} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr}\cos\theta & L_{sr}\cos\phi_1 & L_{sr}\cos\phi_2 & -1/C & 0 \\ L_{sr}\cos\theta & L_r & -(1/2)L_{mr} & -(1/2)L_{mr} & 0 & \sqrt{3}L_{sr}\cos\phi_6 \\ L_{sr}\cos\phi_1 & -(1/2)L_{mr} & L_r & -(1/2)L_{mr} & 0 & \sqrt{3}L_{sr}\cos\phi_4 \\ L_{sr}\cos\phi_2 & -(1/2)L_{mr} & -(1/2)L_{mr} & L_r & 0 & \sqrt{3}L_{sr}\cos\phi_7 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & \sqrt{3}L_{sr}\cos\phi_6 & \sqrt{3}L_{sr}\cos\phi_4 & \sqrt{3}L_{sr}\cos\phi_7 & 0 & 2L_{ss}+L_L \end{bmatrix}^{-1} \times$$

$$\begin{bmatrix} -r_s & L_{sr}\omega\sin\theta & L_{sr}\omega\sin\phi_1 & L_{sr}\omega\sin\phi_2 & -1/C & 0 \\ L_{sr}\omega\sin\theta & -r_r & 0 & 0 & 0 & \sqrt{3}L_{sr}\omega\sin\phi_6 \\ L_{sr}\omega\sin\phi_1 & 0 & -r_r & 0 & 0 & \sqrt{3}L_{sr}\omega\sin\phi_4 \\ L_{sr}\omega\sin\phi_2 & 0 & 0 & -r_r & 0 & \sqrt{3}L_{sr}\omega\sin\phi_7 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sqrt{3}L_{sr}\omega\sin\phi_6 & \sqrt{3}L_{sr}\omega\sin\phi_4 & \sqrt{3}L_{sr}\omega\sin\phi_7 & 0 & -(2r_s+R_L) \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{ar} \\ i_{br} \\ i_{cr} \\ Q \\ i_{bs} \end{bmatrix} \quad (46)$$

3. Simulation results

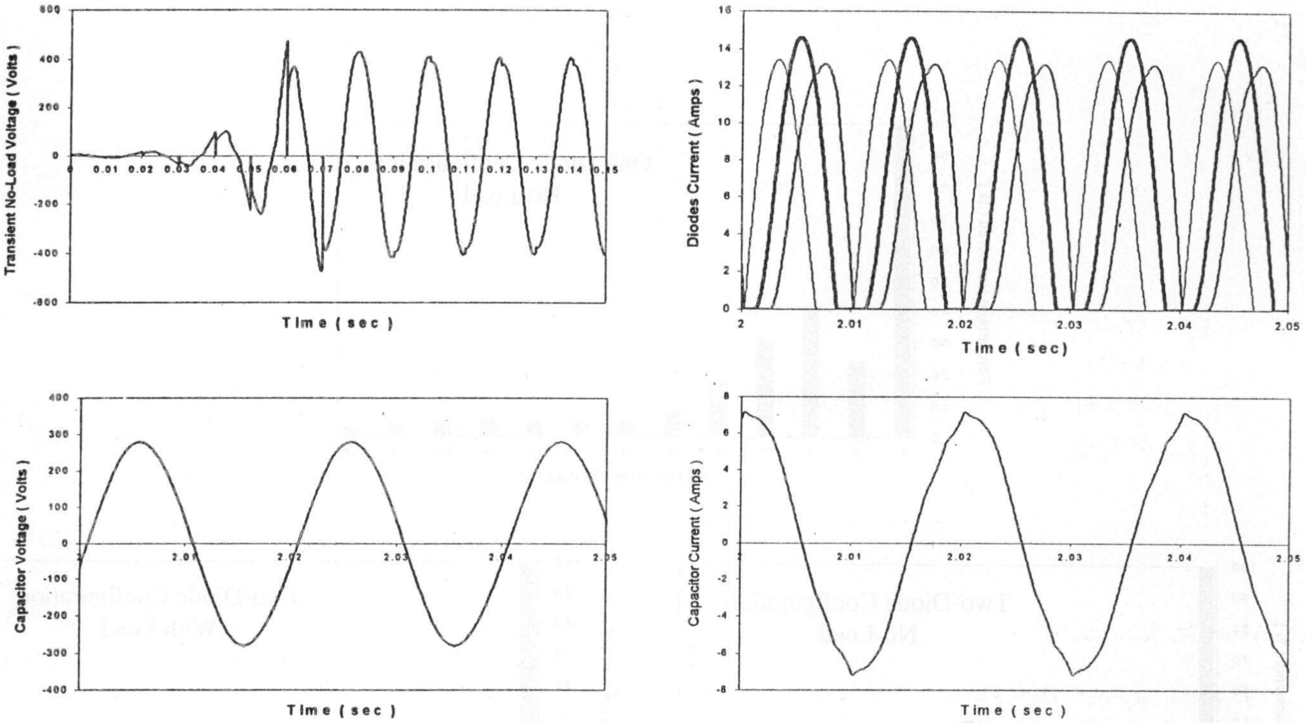
Unfortunately the rotor star point of the available machine is unreachable, therefore only simulation results are possible. The machine used is mentioned in part I [6].

A computer program written in Pascal was developed for simulation purposes. The program is used for predicting the performance of the BSESPSG. Fig. 3 shows the simulation results of the proposed diode configuration for no–load and load conditions, with an excitation capacitor C = 80μF. The load used is an inductive load having the following parameters : R_L = 55 Ω & L_L = 16.58 mH . It is clear that a large improvement has occurred as a result of using this new diode configuration, when compared with the case of two–diode configuration given in part I [6].

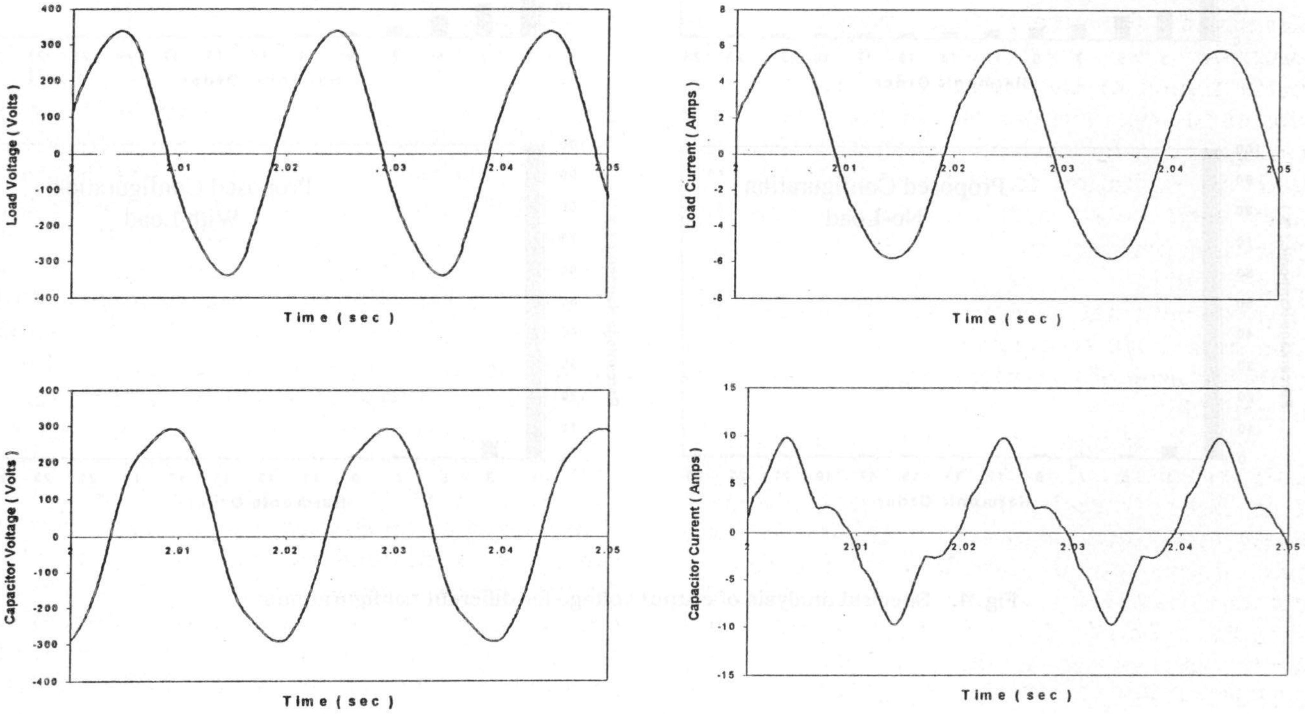
Fig. 4, shows the spectral analysis of output voltage for different configurations. This figure reveals that the new proposed diode configuration has drastically improved the output voltage waveform. The harmonic content has been reduced from 9.391%, 7.758%, 5.063%, 3.797%, 2.997% and 2.103 for the case of two–diodes to 3.744%, 1.477%, 0.783%, 0.988%, 0.67% and 0.578% for the case of three–diodes, for 3rd , 5th , 7th , 9th , 11th and 13th , respectively.

Fig. 5 shows the effect of changing machine parameters on spectral analysis of output voltage. A further reduction in harmonics content has been realized when using a machine with modified parameters [$M_{unsaturated}$ = 0.75*0.28648 H , x_{Lr} = 0.75*0.246 Ohm , x_{Ls} = 0.75*2.93 Ohm]. This improvement is 23% reduction in 3rd harmonic component over unmodified machine from 3.744% to 2.891%.

The harmonic content improvement can be explained as follows: fig. 6 shows the variation of maximum magnetizing current I_M for two–diode configuration and the new proposed diode configuration. This variation is between 6.59A & 5.9A for the two–diodes, while for the three–diodes it is between 4.87A & 4.45A for the case of the original machine, and is between 3.17A & 2.94A for the modified parameters. This smaller variation in I_M means more steady magnetizing current which improves the output voltage waveform. Also, fig. 6 shows one cycle of maximum magnetizing current , I_M , variation depicted on the I_q – I_d plot. A quick look at these characteristics show that the locus for each of the above mentioned cases is getting smaller for the proposed diode configuration. A further improvement for output voltage waveform occurs for the machine with modified parameters showing even a smaller locus. Therefore, an improvement in the output waveform could be expected by looking at the I_M variation and/or I_q – I_d locus.



No-Load



Load

Fig. 3. Simulation results of proposed configuration for no-load & load conditions.

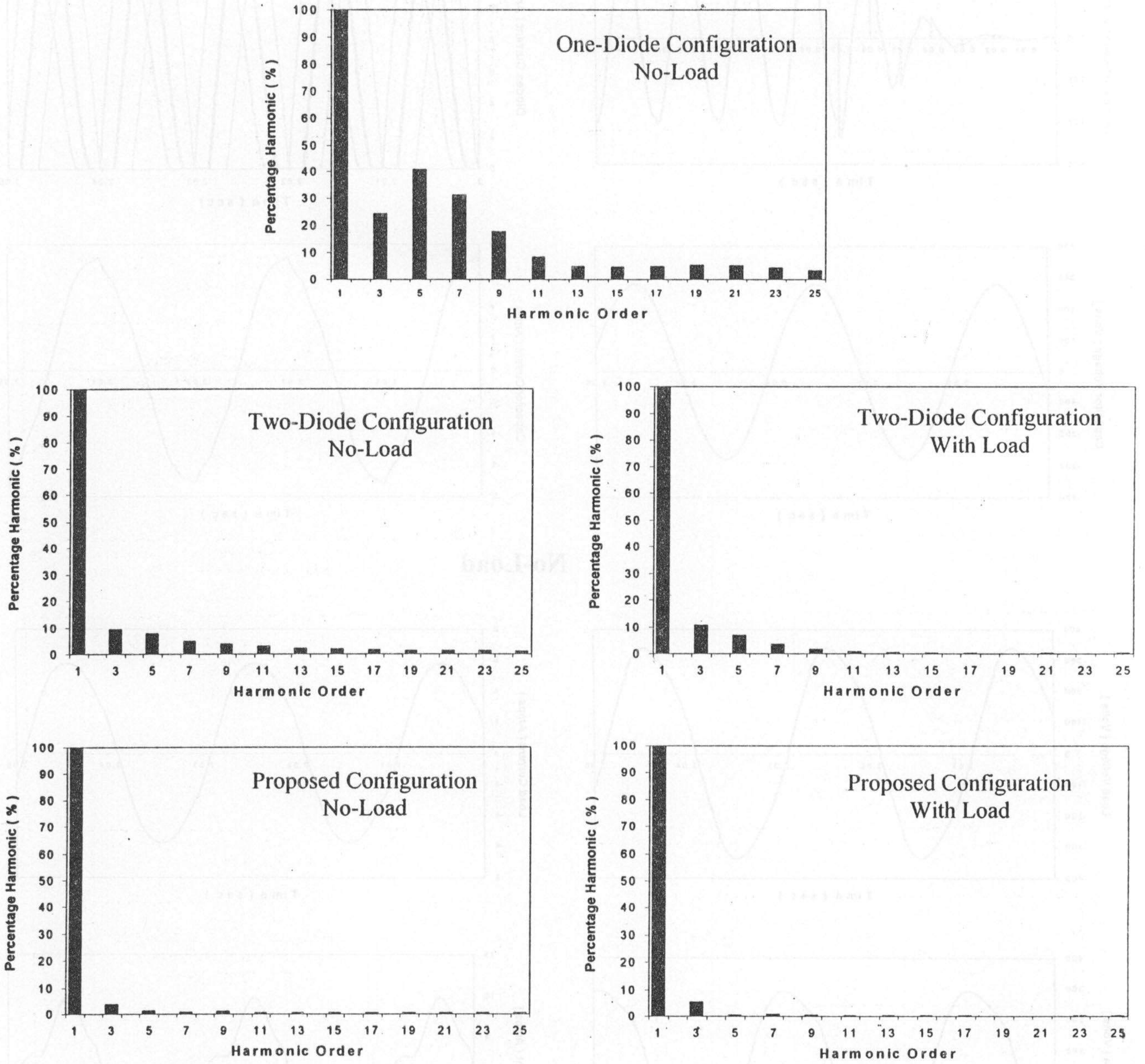


Fig. 4. Spectral analysis of output voltage for different configurations.

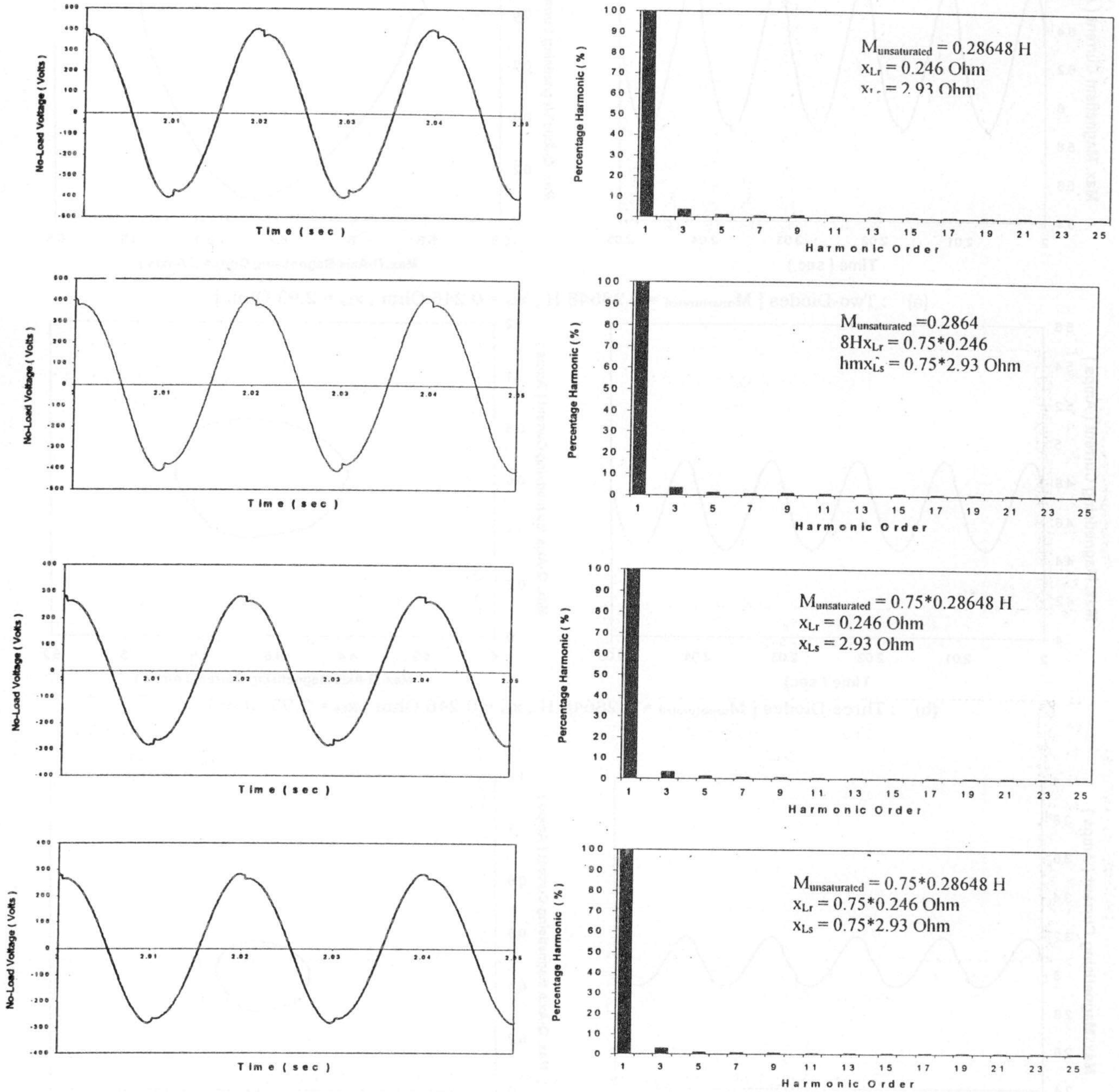
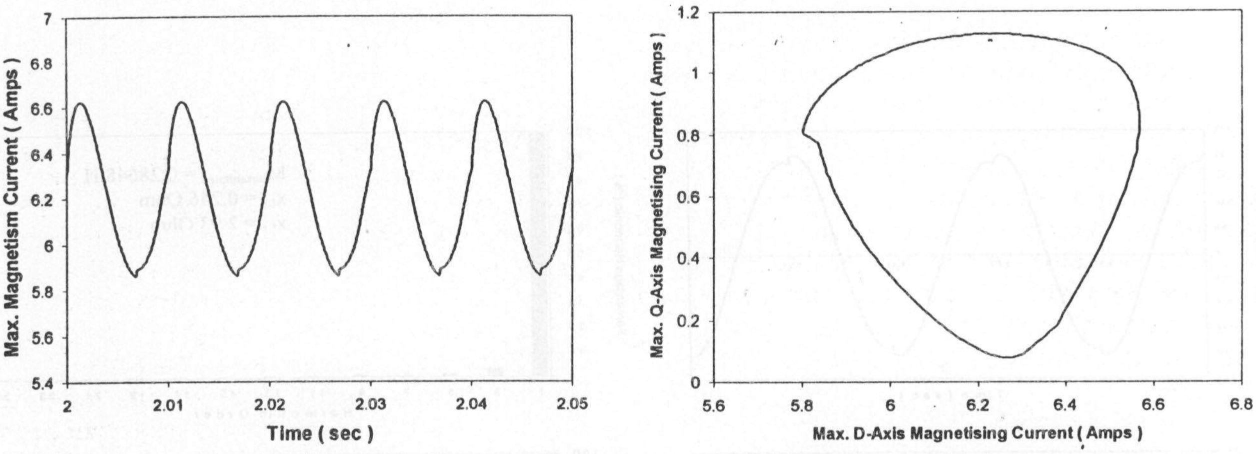
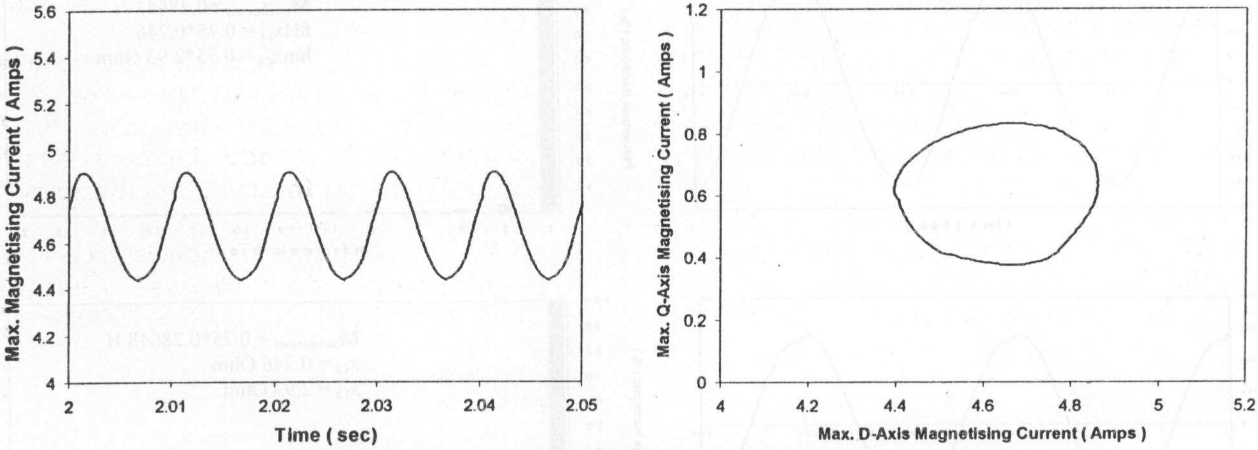


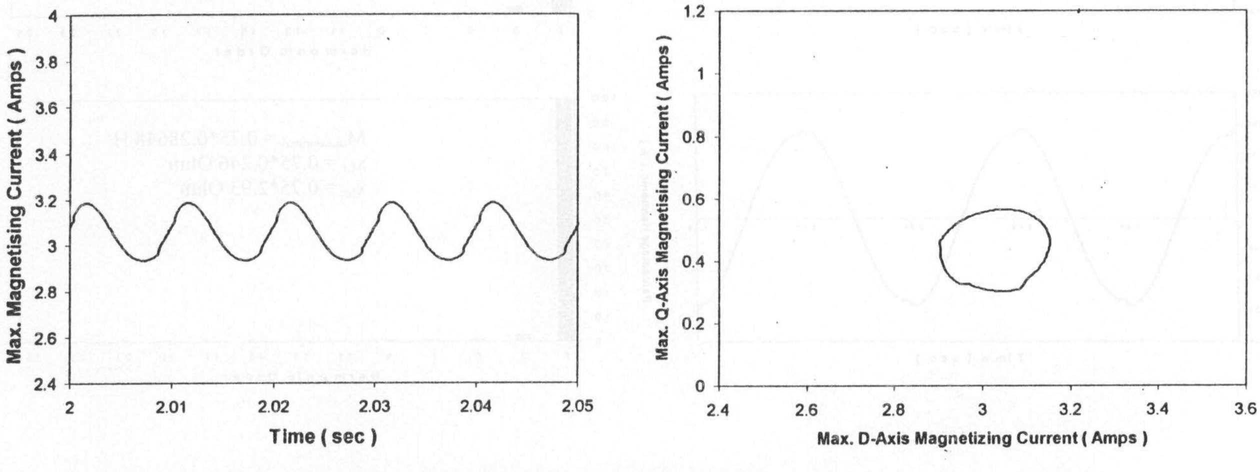
Fig. 5 Effect of changing machine parameters upon spectral analysis of output voltage



(a) : Two-Diodes [$M_{unsaturated}$ = 0.28648 H , x_{Lr} = 0.246 Ohm , x_{Ls} = 2.93 Ohm]



(b) : Three-Diodes [$M_{unsaturated}$ = 0.28648 H , x_{Lr} = 0.246 Ohm , x_{Ls} = 2.93 Ohm]



(c) : Three-Diodes [$M_{unsaturated}$ = 0.75*0.28648 H , x_{Lr} = 0.75*0.246 Ohm, x_{Ls} = 0.75*2.93 Ohm]

Fig. 6 Effect of changing machine parameters upon magnetising current .

4. Conclusions

In this paper, an analytical model for BSESPSG has been developed using a three-diode configuration in the rotor circuit. The mathematical model is seen to be suitable for predicting the generator performance under transient and steady–state conditions. Self-excitation voltage build up has been introduced. Self-excitation of BSESPSG is achieved by virtue of residual magnetism and an excitation winding where a capacitor is used to provide the leading reactive power required.

The study showed some salient features for the new proposed diode configuration over that using two–diodes, these are :

1) highly improved output voltage waveform,
2) drastic reduction of the harmonic content, and
3) reduced magnetising current, and a smaller variation for maximum magnetising current.

Notations

D1, D2, D3	diodes abbreviations,
V_{D1}, V_{D2}, V_{D3}	diodes voltage, and
i_{D1}, i_{D2}, i_{D3}	diodes current.

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