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DAMPING THE TORSIONAL OSCILLATIONS USING SMES IN POWER SYSTEM

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ABSTRACT

Superconducting magnetic energy storage (SMES) systems store energy in the magnetic field which is created by the direct current. Power is available almost instantaneously from SMES systems. Hence it can be successfully used as FACTs device. In the present paper the effectiveness of SMES for damping the torsional oscillations of synchronous generator is investigated. The mathematical modeling of a regulated synchronous generator, transmission line, turbine generator shaft along with SMES has been done. The SMES unit is connected at the generator terminals. The transmission line is represented by its distributed parameters. The studies have been carried out using D-decomposition technique .A point check for stability is done by frequency scanning method.

KEY WORDS

FACT-Flexible AC transmission, NDS- Negative Damping Stabilizer, EHG- Electro Hydraulic Governor, D-decomposition technique

1. INTRODUCTION

The SMES unit can be applied to be a transmission line stabilizer [7]and load frequency controller[8,9].SMES system is also suggested to damp turbine –generator sub synchronous oscillations along with PID controller [2].In the present paper efforts are made to show the effect of SMES in the presence of EHG and NDS on torsional frequency self excited oscillations zone.

The self excited oscillations of synchronous generator occur under certain conditions in series compensated transmission system. Synchronous machine connected to a power system through transmission lines with high ratio of system resistance /reactance may loose stability due to sustained low frequency self excited oscillations in which case the rotor angle oscillations with respect to infinite bus build up with time. In this form the instability, the masses of turbine and generator move together at the hunting frequency (0.2 to 2Hz) depending upon the inertia of the sets and the independence of the system. High frequency self-excited oscillations may also occur when the circuit resistance falls below a certain value. Because of the interaction of shaft torsional mode and electrical resonance modes self excited torsional oscillations may take place. The turbine generator rotor masses oscillate relative to one another at one or more of the natural frequencies. Actual loss of stability depends on the system external resistance, mechanical damping and rotor resistance. The border values of the total resistance Re (Re=Ra +R, R is Transmission line resistance) at different values of series capacitor reactance below or above which the system breaks respectively in to high frequency or low frequency self excited oscillations may be plotted in the form of a stability boundary of self excited oscillations in Xc–Re plane.(Figure in Appendix1) The natural frequency of the shaft can be determined from the spring mass model of the turbine generator set.

In the present paper the power system under consideration consist of a synchronous generator connected to series and shunt compensated transmission lines with distributed parameters.(Fig.1). A SMES unit is connected to the generator terminals .Torsional dynamics of turbine generator has been considered and modeled along the SMIB systems. The investigations have been carried out on 500 Km 50 Hz, system. Since the characteristic equation of the system with distributed parameters is transcendental the stability studies have been carried out by using D-decoposition technique.

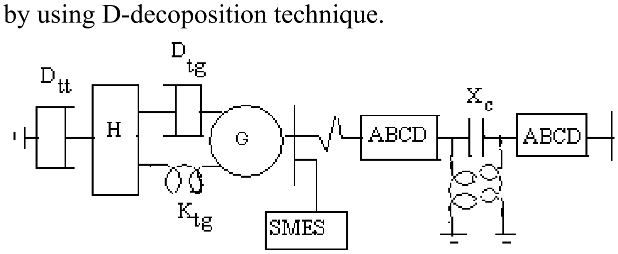


Fig.1. System considered with SMES

2. SYSTEM MODELING

Park's synchronous machine equations using standard assumptions and conventional notations are as follows[1]:

$$M \ddot{\delta} + D_m \dot{\delta} = P_m - P_e \quad (1)$$

Neglecting D_m, the damping factor, equation (1) can be modified as

$$Mp^2\delta = P_m - P_e \quad (2)$$

The main components of SMES system are the super conducting coil and two sets of six pulse bridge power converters which are fed from three phase transformer as shown in Fig.2. Considering the presence of SMES equation may be rewritten as [11]:

$$M p^2 \delta = P_m - P_e - P_{sm} \quad (3)$$

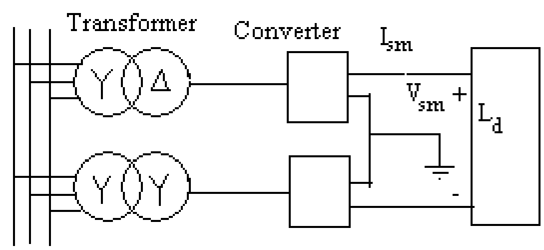


Fig.2. Main components of SMES System

Where the bridge output power P_{sm}, which may be released or absorbed, may be defined as

$P_{sm} = V_{sm} I_{sm}$

V_{sm} and I_{sm} are the voltage and currents of superconducting inductor as shown in Fig.2.

The voltage impressed up and down by changing the firing angle of the thyrister in the bridge circuit in order to achieve the desired power interchange. The phase angle between the voltage and current on the AC side of the converter is 90º when no energy is transferred and is about 180º for maximum discharge. The charge and discharge may be controlled by firing angle α. The bridge current Ism is not reversible. Hence the power is a function of Δα [2].Further Ism and change in Vsm may be defined as follows:

$$\Delta V_{sm} = \frac{K_a}{1+sT_a}\Delta\alpha \quad (4)$$

$$I_{sm} = \frac{1}{Ld}\int_{t_0}^{t} V_{sm} d_\tau + I_{sm0} \quad (5)$$

Where I_{sm0} is the initial current of the superconductor. The energy stored (W_{sm}) in the superconductor coil is

$$W_{sm} = W_{sm0} + P_{sm}(\tau)dt \quad (6)$$

Where as W_{sm0} is the initial energy in the inductor and may be defined as

$$W_{sm0} = \frac{1}{2} Ld I_{sm0}{}^2 \quad (7)$$

The Vsm is controlled continuously depending on the measured speed deviation of the generator rotor [2] .Hence

$$\Delta V_{sm} = \frac{K_a}{1+sT_a}\Delta\omega \quad (8)$$

Small displacement equation may be written as follows. [1]:

$$\Delta P_m = Mp2\,\Delta\delta + \Delta P_e + \Delta P_{sm} \quad (9)$$

$$\Delta P_{sm} = \Delta V_{sm} I_{smo} + V_{smo}\Delta I_{sm} \quad (10)$$

Substituting $V_{smo} = 0$

$$\Delta P_{sm} = \frac{K_a I_{smo}\Delta\omega}{(1+pT_a)} \quad (11)$$

$$\Delta V_t = \frac{V_{d0}}{V_{t0}}\Delta V_d + \frac{V_{q0}}{V_{t0}}\Delta V_q \quad (12)$$

Small displacement equations for the d-q axis voltage components of the machine in terms of d-q axis current components of the line parameters based on the system

$$\begin{bmatrix}\Delta V_d \\ \Delta V_q\end{bmatrix} = [Z1]\begin{bmatrix}\Delta I_d \\ \Delta I_q\end{bmatrix} + [Z2][\Delta\delta] \quad (13)$$

$$\Delta P_e = V_{do}\Delta_{id} + i_{do}\Delta V_d + i_{qo}\Delta V_q + \Delta V_q + V_{qo}\Delta i_q \quad (14)$$

Further using transfer function of EHG $g_D(p)$[5]

$$\frac{T_m}{\Delta(p\theta)} = -g_D(p) \quad (15)$$

$$\Delta T_m = -g_D(p)\, p\Delta\delta \quad (16)$$

$$\Delta P_m = \Delta(p\theta)\Delta T_m \quad (17)$$

$$\Delta P_m = -\, g_D(p)\, p^2\Delta\delta \quad (18)$$

Equations for torsional dynamics are as follows:

$$\begin{bmatrix}(\Delta T_{el} + \Delta T_m) \\ 0\end{bmatrix} = \begin{bmatrix}A_{33}{}' A_{34} \\ A_{43} A_{44}\end{bmatrix}\begin{bmatrix}\Delta\delta \\ \Delta\delta_t\end{bmatrix} \quad (19)$$

where

$$A_{33}{}' = H_g p^2 + D_{gg} D_{tg} p + K_{tg}$$

$$A_{34} = A_{43} = -(D_{tg} p + K_{tg})$$

$$A_{44} = H_t . p^2 + (D_{tt} + D_{tg})p + K_{tg}$$

Equations (9-19) are homogeneous expressions describing the behavior of the system under investigation and can be written in the matrix form

$$[A]\,[\Delta X] = 0 \quad (20)$$

Where $[\Delta X] = [\Delta i_d\ \Delta i_q\ \Delta\delta]$

Data used for the system are given in Appendix 1. The characteristic equation is given by

$$|A| = 0 \tag{21}$$

$$K(p)R_e^2+M(p)R_e+N(p)=0 \tag{22}$$

For various values of Xc the border values of Re are obtained and stability limit curves are plotted in X_C–R_e plane. Coefficient of equation (22), K(p), M(p) and N(p) are given in Appendix 3,4.

3. RESULTS AND DISCUSSION

3.1 Comparison with unregulated system

The stability boundaries of self excited oscillations of an unregulated conventional synchronous generator, feeding power to an infinite bus in the presence of SMES are shown in Fig.3. It is observed that SMES is effective because it increases the stable area and hence the more value's of Re in the stable region and significantly in suppressing the self-excited oscillations in torsional frequency region. The high frequency and low frequency stability limit curves remain almost the same as for the unregulated system. Low, high and torsional frequencies are shown in the figure.

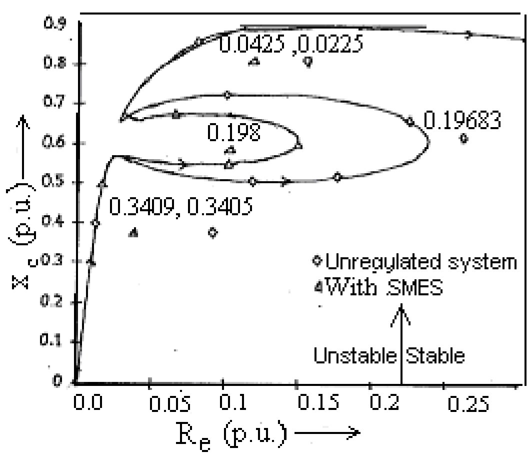


Fig 3. Stability limit curves for the unregulated system with SMES

3.2 Comparison with other controllers

The effect of SMES when provided with other controllers like NDS and EHG is also examined. Stability limi curves are plotted in Re-Xc plane

3.2.1 SMES and EHG

The effect of SMES and EHG on self excited oscillations of synchronous generator, feeding power to long transmission line to infinite bus is shown in Fig.4. It is is not found significantly effective in suppressing high frequency and low frequency oscillations.

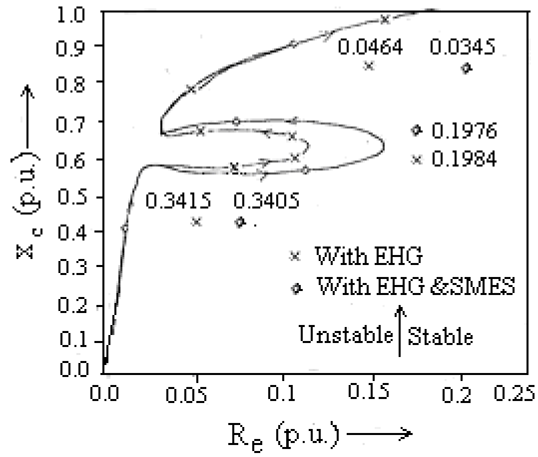


Fig.4 Stability limit curves with SMES & EHG

3.2.1 SMES and EHG

The effect of SMES and EHG on self excited oscillations of synchronous generator, feeding power to long transmission line to infinite bus is shown in Fig.4. It is is not found significantly effective in suppressing high frequency and low frequency oscillations.

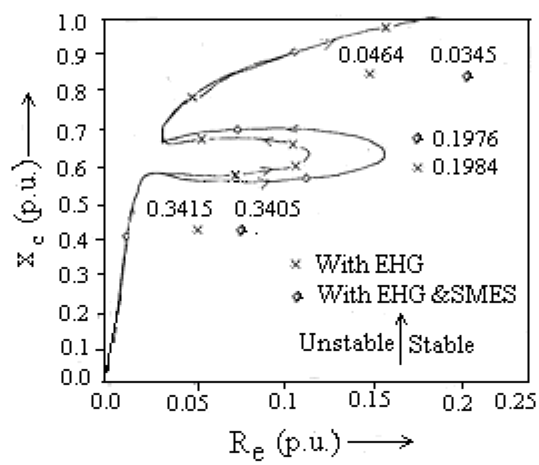


Fig.4 Stability limit curves with SMES & EHG

3.2.2 SMES and NDS

The transfer function of NDS [5] is considered to get the final characteristic. The stability limit curves for the synchronous generator provided with NDS and SMES are plotted in Fig.5. It is observed that the stable area in the neighborhood of the additional loop of stability limit curve due to torsional interaction increases when both SMES and NDS are present compared to what it is when NDS is present. High frequency oscillations are completely suppressed. The stability limit curve of low frequency oscillations lifts up when both SMES and NDS are acting together giving more stability region than the region available when NDS is present.

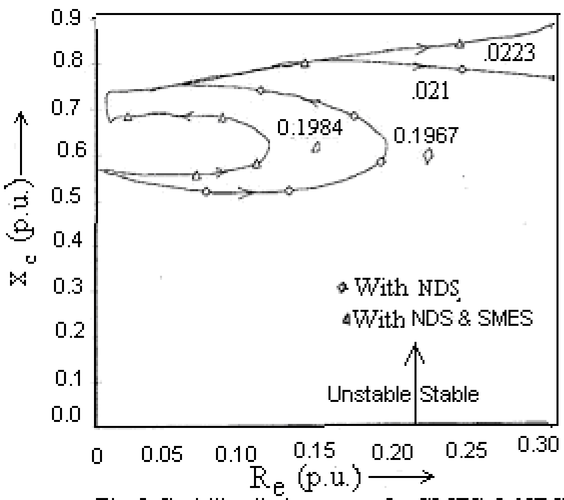


Fig 5. Stability limit curves for SMES & NDS

3.2.3 SMES, EHG and NDS

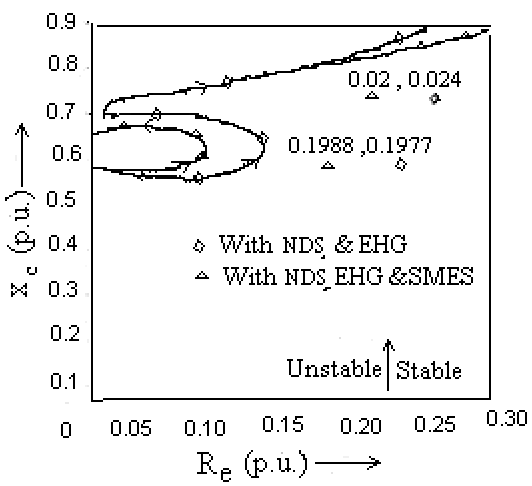


Fig 6. Stability limit curves with NDS & EHG

The effect of SMES when the system is provided with NDS and EHG is shown in Fig.6. It is observed that SMES improves further the stable area in the neighborhood of the additional loop of stability limit curve in the torsional frequency zone and in low frequency zone in comparison with when NDS and EHG are acting ,where as no change is found in boundary of high frequency oscillations. Fig.7 give a comparison between the stability limit curve in X_C and R_e plane when various controllers are present if the SMES is also present along with other controllers it has no adverse effect and helps in further improving the stable area in the neighborhood of the stability boundary of torsional and low frequency oscillations . The maximum value of R_e below which system becomes unstable due to torsional oscillations for various combinations of controllers is given in Table 1. It can be seen from Table1 that the best results for obtaining stable zone are observed when SMES , EHG and NDS are present simultaneously.

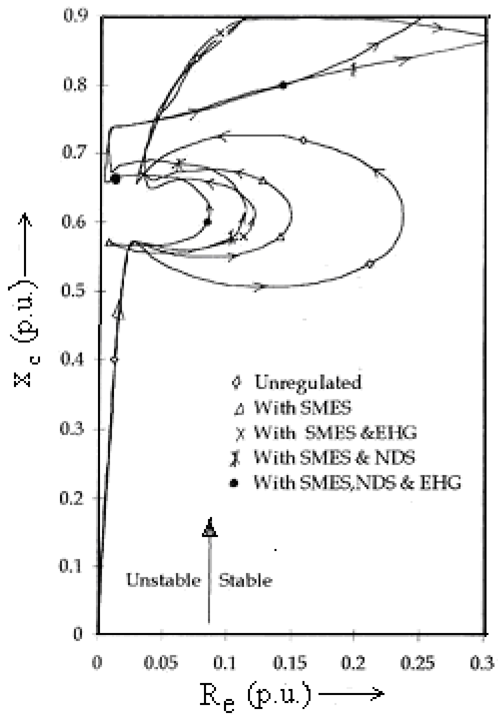


Fig 7. Stability limit curves with SMES

Table 1

Maximum value of resistance R_{max}(pu) and X_c(pu), corresponding to various combinations of controllers.

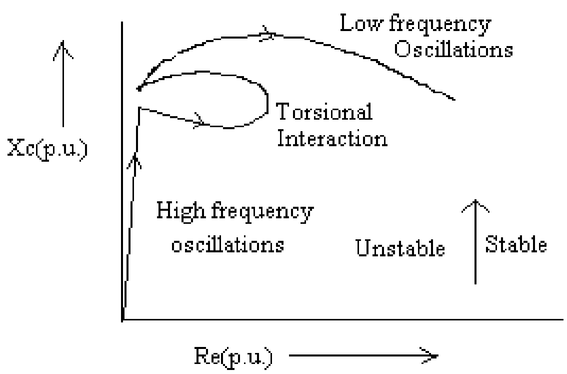
S. No.	X_c(pu)	R_{max}(pu)	Remarks
1.	0.6	0.236	Unregulated
2.	0.62	0.1909	With NDS
3.	0.6	0.164	With EHG
4.	0.6	0.148	With SMES
5.	0.62	0.119	With SMES & EHG
6.	0.62	0.1134	With SMES & NDS
7.	0.62	0.0854	With SMES, NDS & EHG

4. CONCLUSION

A mathematical modeling of synchronous generator connected to long transmission line (500Km) with SMES at generating end has been developed .The transmission line is represented by its distributed parameters. Torsional dynamics is also considered .It has been found that SMES is an effective shunt operated FACT controller to increase the torsional region in X_C –R_e plane. The stability zone in the neighborhood of low frequency oscillations boundary is also increased. SMES may be used with conventional controllers like NDS and EHG, this gives no adverse effect but helps in improving the stable area. In the present paper it can be concluded that at torsional frequencies Xc/Re ratio may be improved because lower value of Re is permissible without loss of stability as shown in Table.1.

APPENDIX

1.



Self- Excited Oscillations with Torsional Interaction
(Free to scale)

2. Data used in the System

l = 500km ,V1=1.0,α = 0.00106 rad./km, $i_d = 0$, i_q = 0.25(lag), $T_{do}' = 2000$, $T_{do}'' = 18.75$, $T_e = 800$, $T_s = 800$, $X_d = 1.0$, $X_q = 0.6$, $T_d' = 500$, $T_d'' = 15$, $T_{ee} = 628.0$, X_t = 0.15,$T_{qo}'' = 42.8$,$T_w = 389.36$, $H_g = 1559$, $H_t = 935.9$, T_q'' = 15, T_1=T_2=31.4,T_{kd} = 9.75, $D_{gg} = 0$, K_{tg} = 22.5,U_{nde} = 100,$D_{tt} = D_{tg} = 0.6$,T_{nd1} = 12.56,T_{nd2} =6.28, T_{nd3} = 4.17, T_{nd4} = 0.0, I_{smo} = 0.6495, Ka=1.83, Ta=0.0816s.

3. Elements of Characteristic of Equation (20)

$A_{11} = -B_6(p)h(p)+B_{n1}(p)h_1(p)+R_e\,(h_1(p)i_{qo}-h(p)S_d)$ $+Z''(p)+X_d(p)$

$A_{12} = -\,B_7(p)h(p)+B_{n2}(p)h_1(p)+B_8(p) + R_e(1-h\,(p) +$ $B_{n3}(p)h_1(p)i_{do})$

$A_{13} = -\,R_e(B_{n4}(p)h(p)-B)_{n5}(p)h_1(p)+i_{do})-$ $B_9(p)h(p)+Bn_3(p)h_1(p)+B_{10}(p)$

$A_{21} = R_e + B_3(p)$

$A_{22} = -\,pR_e + B_3(p)$

$A_{23} = -\,(i_{qo} + pi_{do})\,R_e + B_5(p)$

$A_{31} = -i_{do}R_e+B_{11}(p)$

$A_{32} = (i_{qo}-pi_{do})R_e+B_{12}(p)$

$A_{33} = -pi^2_{do}Re+B_{12}(p)$

Where

$B_1(p) = V_{qo}-i_{qo}Z'(p)-i_{do}\,Z''(p)$

$B_2(p) = V_{do}+i_{qo}Z''(p)-i_{do}Z'(p)$

$B_3(p) = Z''(p)-pZ''(p)+r_\alpha$

$B_4(p) = -Z''(p)-pZ'(p) - (p^2+1)X_q\,(p) - pr_\alpha$

$B_5(p) = B_1(p)+pB_2(p)+p^2\,\varphi_{do}+p\varphi_{qo}$

$B_6(p) = S_dZ'(p)+S_qZ''(p)$

$B_7(p) = S_qZ'(p)-S_dZ''\,(p)$

$B_8(p) = Z'(p)+pX_q\,(p)+r_\alpha$

$B_9(p) = S_dB_1(p)-S_qB_2(p)$

$B_{10}(p) = -B_2(p)-pV_{qo}-pr_\alpha i_{qo}$

$B_{11}(p) = i_{do}Z'(p)+(i_{qo}-pi_{do})Z''\,(p)+V_{do}+2i_{do}r_\alpha$

$B_{12}(p) =V_{qo}i_{do}(Z''(p)+pZ'(p)+p^2X_q(p)$
$+pr_\alpha)+\,i_{qo}(Z'(p)+pX_q(p)+2r_\alpha)$

$B_{13}(p) = i_{do}B_1(p)-(i_{qo}-pi_{do})B_2(p)+J(p)$

$J(p) = H_Rp2+g_D(p)\,p+p^2\,i_{do}(V_{qo}+i_{qo}r_\alpha)-T_{elo}\,p$

$B_{n1}(p) = Z'(p)i_{qo}-Z''(p)i_{do}-V_{qo}$

$B_{n2}(p) = -\,Z''(p)i_{qo}-Z'(p)i_{do}+V_{do}$

$B_{n3}(p) = B_1(p)i_{qo}+B_2(p)i_{do}$

$B_{n4}(p) = S_di_{qo}-S_qi_{do}$

$B_{n5}(p) = i^2_{do}+i^2_{qo}$

4. Coefficients of Equation (22)

$K(p) =-X_1(p)h(p)+X_2(p)-h_1(p)X_7(p)$

$M(p) = -X_3(p)h(p)+X_4(p)-h_1(p)X_8(p)$

$N(p) = -\,X_5(p)h(p)+X_6(p)-h_1(p)X_9(p)$

$X_1(p) =B_6(p)i^2_{qo}-\,S_qB_{16}(p)-B_7(p)i_{qo}i_{do}$
$-(S_di_{qo}+S_qi_{do})B_{18}(p)+i_{qo}B_9(p)$

$X_2(p) = i_{do}B_{18}+B_{10}(p)i_{qo}-\,B_{16}(p)$
$-B_8(p)i_{qo}i_{do}+(X_d(p)+Z''(p))i^2_{qo}$

$X_{.3}(p) = B_6(p)B_{14}(p)+\,B_{15}(p)\,S_d$
$-B_7(p)B_{16}(p)-B_{17}(p)\,S_q+S_qi_{do}\,B_{19}(p)$
$+B_9(p)B_{18}(p)-S_di_{qo}B_{19}(p)$

$X_4(p) = (X_d(p)+Z''(p))B_{14}(p)-B_8(p)B_{16}(p)-B_{17}(p)$
$+B_{19}(p)i_{do}+B_{10}(p)B_{18}(p)$

$X_5(p) = B_6(p)B_{15}(p)-B_7(p)B_{17}(p)+B_{19}(p)B_9(p)$

$X_6(p) = (X_d(p)+Z''(p))B_{15}(p)-B_8(p)B_{17}(p)+B_{10}(p)+B_{19}(p)$

$$X_7(p) = -(B_{n1}(p)i_{qo}^2+B_{14}(p)i_{qo}+B_{16}(p)i_{do}$$
$$-B_{n2}(p)i_{qo}i_{do}+B_{n3}(p)i_{qo}-B_{18}(p)B_{n5}(p))$$
$$X_8(p) = -(B_{15}(p)i_{qo}+B_{14}(p)B_{n1}(p)+B_{17}(p)i_{do}$$
$$+B_{18}(p)B_{n3}(p)-B_{n2}(p)B_{16}(p) -B_{n5}(p)\ B_{19}(p))$$
$$X_9(p) = -(B_{15}(p)B_{n1}(p)-B_{17}(p)B_{n2}(p)+B_{19}(p)B_{n3}(p))$$

$B_{14}(p)$ to $B_{19}(p)$ are as follows:

$$B_{14}(p) = -pB_{13}(p)-B_4(p)pi_{do}^2-i_{qo}B_5(p)+pi_{do}B_5(p)$$
$$+ B_{12}(p)i_{qo}+B_{12}(p)pi_{do}$$
$$B_{15}(p) = B_4(p)B_{13}(p)-B_5(p).B_{12}(p)$$
$$B_{16}(p) = B_{13}(p)-pB_3(p).i_{do}^2-B_5(p)i_{do}-i_{qo}B_{11}(p)+pi_{do}B_{11}(p)$$
$$B_{17}(p) = B_3(p)B_{13}(p)-B_5(p)B_{11}(p)$$
$$B_{18}(p) = B_{12}(p)+i_{qo}B_3(p)-B_3(p).p\ i_{do}-B_4(p).i_{do}+p.B_{11}(p)$$
$$B_{19}(p) = B_3(p)B_{12}(p)-B_4(p)B_{11}(p)$$

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