Use of Matrix Converter as Slip Power Regulator in Doubly-fed Induction Motor Drive for Improvement of Power Quality

Arup K. Dalal, Prasid Syam, and Ajit K. Chattopadhyay, *Fellow*, *IEEE*

***Abstract*-- This paper reports the results of a simulation study of using a matrix converter(MC) to replace the line commutated cycloconverter as a static frequency changer in a slip power controller for induction motor speed control from power quality point of view. A slip power controller is required either to inject or to extract the slip power from the rotor of a doubly fed induction motor. Use of the Matrix Converter (MC) in place of the cycloconverter improves the drive performance by the generation of nearly sinusoidal injected voltage to the motor, sinusoidal input and output currents and adjustable input power factor for any loading condition. Simulation has been done in MATLAB program and results displayed for both sub- and super-synchronous speed of a laboratory motor.**

***Index Terms*— indirect method, induction motor, matrix converter, slip-power, space-vector pulse width modulation.**

I. NOMENCLATURE

H = machine inertia constant in per unit

i_{qs} = stator q-axis current in per unit

i_{ds} = stator d-axis current in per unit

i_{os} = stator o-axis current in per unit

i'_{qr} = rotor q-axis current in per unit

i'_{dr} = rotor d-axis current in per unit

i'_{or} = rotor o-axis current in per unit

r_s = stator resistance in per unit

r'_r = rotor resistance in per unit

T_L = load torque in per unit

v_{qs} = stator q-axis voltage in per unit

v_{ds} = stator d-axis voltage in per unit

v_{os} = stator o-axis voltage in per unit

v'_{qr} = rotor q-axis voltage in per unit

v'_{dr} = rotor d-axis voltage in per unit

v'_{or} = rotor o-axis voltage in per unit

w_b = frequency of the supply (base frequency)

x_s = stator leakage reactance in per unit

x'_r = rotor leakage reactance in per unit

x_m = magnetizing inductance in per unit

$x_{aq} = 1/(1/x_m + 1/x_s + 1/x'_r)$;

$x_{ad} = x_{aq}$

φ_{qs} = stator q-axis flux linkage in per unit

φ_{ds} = stator d-axis flux linkage in per unit

φ_{os} = stator o-axis flux linkage in per unit

φ'_{qr} = rotor q-axis flux linkage in per unit

φ'_{dr} = rotor d-axis flux linkage in per unit

φ'_{or} = rotor o-axis flux linkage in per unit

II. INTRODUCTION

THIS paper reports the results of a study of using a matrix converter(MC) to replace the line commutated cycloconverter as a static frequency changer in a slip power controller for induction motor speed control from power quality point of view. A slip power controller is required either to inject or to extract the slip power from the rotor of a doubly fed induction motor. Slip power controlled high power drives using three phase doubly fed induction motors have found applications in large capacity pumps and fan drives, variable-speed wind energy systems, shipboard

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VSCF (variable-speed/constant-frequency) systems, variable-speed hydro pumps/generators and utility system flywheel energy storage systems [1]-[3]. In a static Scherbius drive, with bi-directional slip power flow, slip power can be controlled in both the sub-synchronous and super-synchronous ranges of speed. A line commutated cycloconverter acts as a static frequency changer in the drive system [14]. The major power quality related problems for a line commutated cycloconverter are: input current contains low frequency inte-harmonics and sub-harmonics and thus affects the utility, input power factor is always lagging irrespective of the load power factor and output voltage contains sub-harmonics for larger input to output frequency ratio.

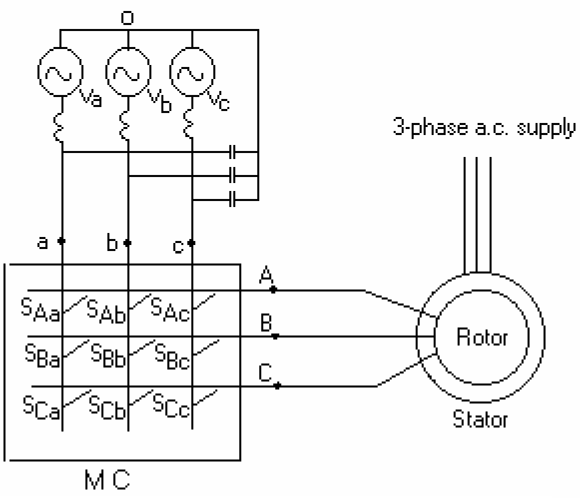

Fig. 1. Wound rotor induction motor fed by matrix converter.

The wound rotor induction motor fed by a matrix converter as dealt with in this paper is shown in Fig. 1. The MC provides a slip frequency emf which is injected into the rotor to affect speed control. The speed-torque characteristics are expected to be similar to those of a dc shunt motor and the drive will be inherently stable because of the effective 'speed feedback'. The advantage of this drive apparently are: lower power rating of the speed-control apparatus for a restricted speed range when compared with the primary frequency control, absence of external v/f control, possibility of power factor control, possibility of speed control in both sub- and super- synchronous region beyond the limit for a *naturally commutated cycloconverter,* easy elimination of harmful interharmonics / subharmonics when compared to a line commutated cycloconverter.

The system in Fig.1. has been simulated and sample simulation results are shown here. The operation of the MC to generate a slip-frequency voltage by sequentially switching the phase voltages of main frequency by space vector pulse width modulation(SVPWM) method is taken into account . Simulation is done by MATLAB program. There are two methods for generating SVPWM pulses i) direct method[4] and ii) indirect method[5-12]. In this paper indirect control method is considered for easy implementation in simulation study. A closed-loop speed control of the motor is done using PI controller.

III. SYSTEM OVERVIEW

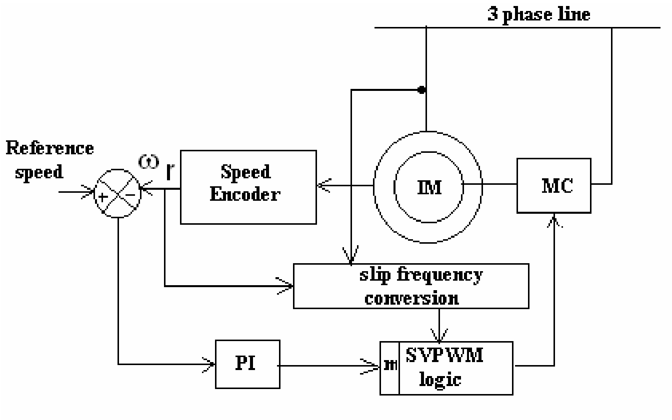

Fig. 2. The control block diagram of the drive system.

The control block diagram of the doubly-fed wound rotor induction motor drive with matrix converter(MC) is shown in the Fig. 2. The speed encoder measures the speed which is compared with the reference speed. The PI controller acts on the speed error and adjusts modulation index(m) of the matrix converter to control the output voltage to be applied across the rotor terminals. This voltage controls the power injection in the rotor winding to control the speed of the motor. The slip which is required to generate SVPWM signal of the matrix converter is calculated with the help of actual speed and synchronous speed (supply frequency).

A. Induction machine model

The state-space equation of the wound rotor induction machine is given below[13].

$$\dot{\varphi} = A\bar{\varphi} + B\bar{u}$$

$$\bar{I} = C\bar{\varphi} + D\bar{u}$$

where ,

$$\bar{\varphi} = \begin{bmatrix} \varphi_{qs} & \varphi_{ds} & \varphi_{os} & \varphi'_{qr} & \varphi'_{dr} & \varphi'_{or} \end{bmatrix}^T$$

$$\bar{u} = \begin{bmatrix} v_{qs} & v_{ds} & v_{os} & v'_{qr} & v'_{dr} & v'_{or} \end{bmatrix}^T$$

$$\bar{I} = \begin{bmatrix} i_{qs} & i_{ds} & i_{os} & i'_{qr} & i'_{dr} & i'_{or} \end{bmatrix}^T$$

The matrices A, B, C and D are elaborated in Appendix-A

B. Indirect method control of matrix converter (MC)

In this method the MC is considered as a combination of a rectifier and an inverter as shown in Fig. 3. So nine switch of MC can be fictitiously split up to 12 switches of voltage source rectifier(VSR) and voltage source inverter(VSI) as shown in Fig. 3.

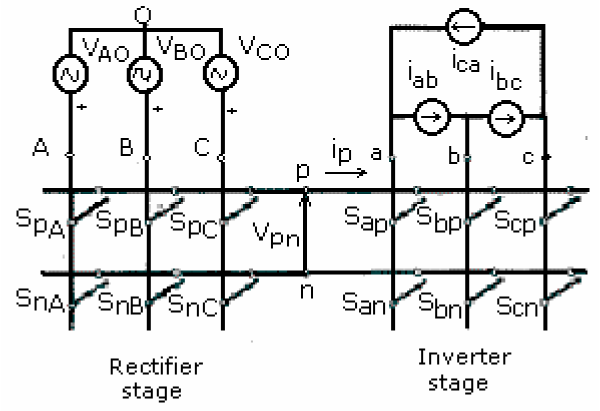

Fig. 3. The indirect modulation model of matrix converter.

C. Space vector modulation

The space vector modulation is simultaneously employed to both VSR and VSI parts of the MC. First the VSI-SVM and VSR-SVM procedures are reviewed. Let us consider VSI part of the circuit in Fig. 3. The VSI is supplied by voltage source $v_{pn} = V_{dc}$. The VSI switches can assume only six allowed combination which yield non-zero output voltages and two combination of zero output voltages. Hence, the resulting output line-voltage space vector defined by

$$\vec{v}_{oL} = \frac{2}{3}\left(\vec{v}_{ab} + \vec{v}_{bc} e^{+j120^o} + \vec{v}_{ca} e^{-j120^o}\right)$$

can assume only seven discrete values, V_o – V_6 as shown in Fig. 4.

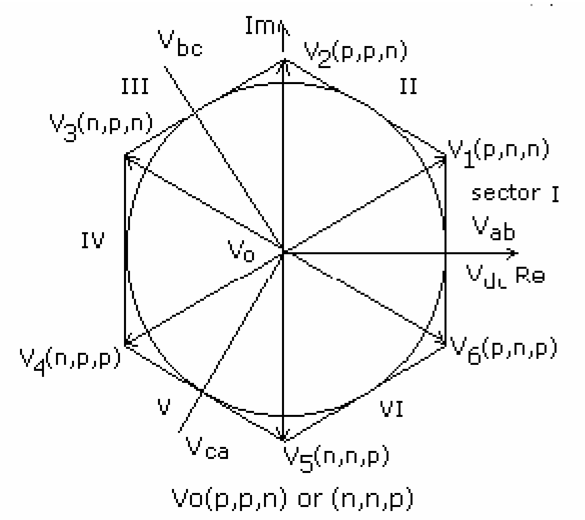

Fig. 4. Inverter voltage hexagon.

Now VSR part of the circuit in Fig. 3. is considered as a standalone VSR loaded by a dc current generator $i_p = I_{dc}$. The VSR input-current SVM is completely analogous to the VSI output voltage SVM as shown in Fig. 5.

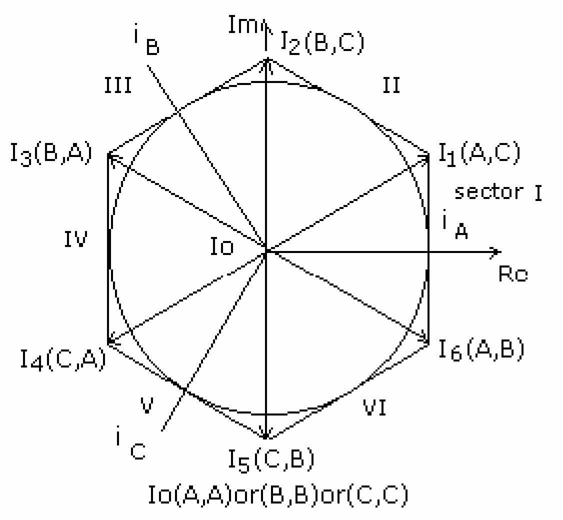

Fig. 5. Rectifier Current hexagon.

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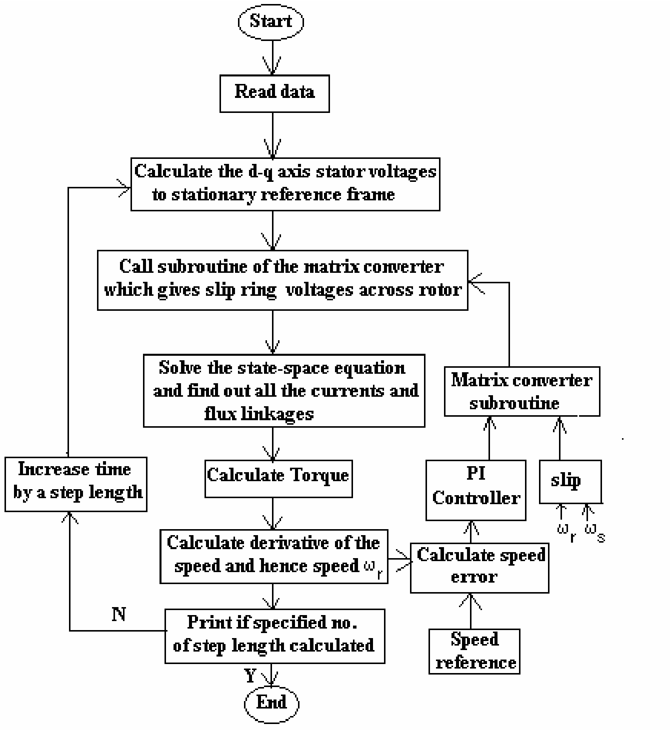

Fig. 6. Flow chart of the simulation program.

IV. SIMULATION

The drive system as shown in Fig. 1. has been simulated using MATLAB simulation software[15]. The program was divided into sections in a Main Program and a subroutine. The flow chart of the program is shown in Fig. 6.

Main program: This program sets the procedure for the computation of the dynamic performance. The initial conditions of the variables used are stated to be zero at zero time. The state variables are taken as both stator and rotor flux linkages. The transient run-up performance under loaded condition is computed over a range of 0.0 to 3 sec. in steps of

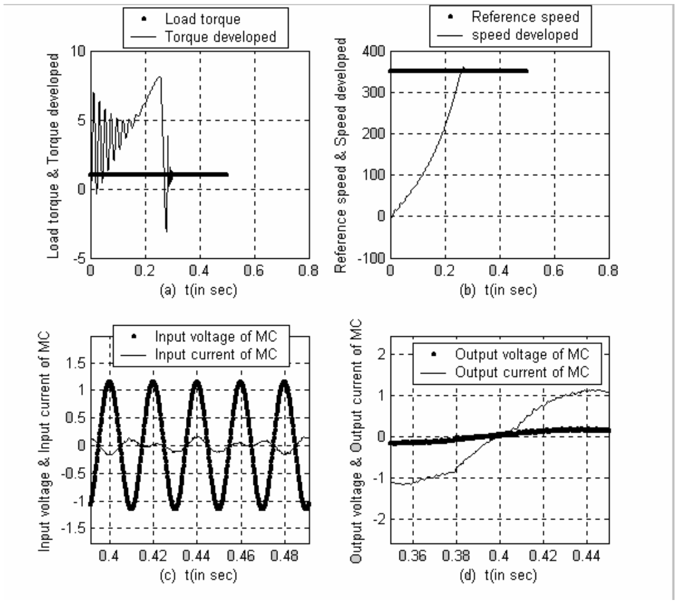

Fig. 7. Simulation result at super-synchronous speed (a) Torque response at start, (b) Speed response at start, (c) Supply side voltage and input current of MC at steady state and (d) output voltage and current of MC at steady state: for $T_L = 1$ p.u. and Speed reference = 350 rad/sec.

0.0002 sec. The 3-phase supply voltages are first transformed into d-q axes in a stationary reference frame. Rotor voltages are deduced with the help of *matrix converter* program written in a subroutine, which is called in each step. The modulation index(m) of the matrix converter is adjusted by the PI controller in the speed feedback loop which in turn calculate the required output voltage of the converter. The stator and rotor currents and flux linkages are calculated by solving the state space equations of the motor. The developed torque is then calculated. The electromechanical dynamic equation is then solved to derive the speed. The slip frequency is calculated as a necessary input to the matrix converter sub-routine

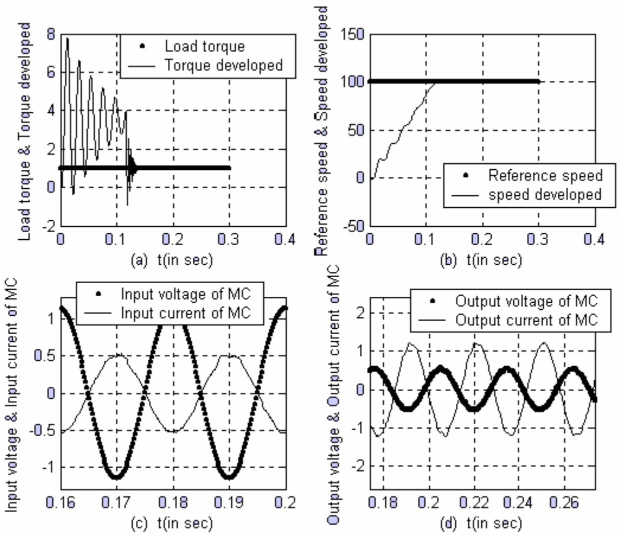

Fig. 8. Simulation result at sub-synchronous speed (a) Torque response at start, (b) Speed response at start, (c) Supply side voltage and input current of MC at steady state and (d) output voltage and current of MC at steady state: for $T_L = 1$ p.u. and Speed reference = 100 rad/sec.

Matrix converter subroutine: This program generates three phase output voltages at a desired (slip) frequency from the input supply voltages to feed power to the rotor. In each step of the main program this sub- routine is called. The inputs to this sub-routine are the supply voltages, angular position of the reference output voltage to calculate the slip, modulation index from the output of the PI controller and angular position of the input current hexagon to adjust input power factor. The basic idea of indirect method applied in SVPWM is to decouple the control of the input current and the control of output voltage. In order to generate the switching patterns for the nine bi-directional switched matrix converter, the two-space vector PWMs are to be combined by multiplying the adjacent vectors together with their duty cycles between the rectifier stage and the inverter stage. As there are six output voltage sectors and six input current sectors, the converter can assume 36 different vectorial states. The output voltage vector and input current vector are rotating at a speed which depends on output frequency and input frequency respectively and with time. At any instant the voltage vector and current vector lies in a particular sector of output and input hexagon respectively. Knowing this, which output phase, is to be connected to which input phase is determined. There are 36 combinations at which the output phases are to be connected to input phases.

V. SIMULATION RESULTS

The rating of the induction motor simulated in the present scheme is 1/3 H.P., 230V, 50 Hz, 1.3A., 1400 rpm. The p.u. parameters of the induction machine are $r_s = 0.032$; $r'_r = 0.0515$; $x_s = 0.042$; $x'_r = 0.042$; $x_m = 0.62$; $H = 0.446$. Two different mode of operation are considered; (1) super-synchronous mode of operation, (2) sub-synchronous mode of operation. Load torque is kept at 1 p.u and reference speeds are 350 rad/sec and 100 rad/sec respectively. The results of the simulation are illustrated in Fig.7. and Fig.8. respectively.

It is seen from Fig.7. and Fig. 8. that the developed speed of the machine attains the reference speed for a given load torque of 1p.u. It is a tracking system with a PI controller. It is further observed that MC input current and voltage are exactly at unity power factor and output current and voltages are very close to unity power factor. Also the voltage injected to the slip rings of induction motor and the rotor current contain very less harmonics improving power quality.

VI. CONCLUSION

The simulation results for the speed control scheme of the doubly-fed induction motor using matrix converter as slip power controller show significant improvement in the power quality of the drive. The input current taken from the supply is almost sinusoidal and the input power factor is unity. This input power factor can be controlled. The output voltage feeding the rotor is also nearly sinusoidal, generating sinusoidal rotor current which improve the conversion efficiency with lesser harmonic heating compared to the cycloconverter-fed drive. The experimental verification of the scheme is now under progress with an IGBT Matrix converter module (ECONOMAC--FM35R12KE3) donated by Eupec, Germany.

VII. APPENDIX

$$A=\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix}$$

$$B=\begin{bmatrix} w_b & 0 & 0 & 0 & 0 & 0 \\ 0 & w_b & 0 & 0 & 0 & 0 \\ 0 & 0 & w_b & 0 & 0 & 0 \\ 0 & 0 & 0 & w_b & 0 & 0 \\ 0 & 0 & 0 & 0 & w_b & 0 \\ 0 & 0 & 0 & 0 & 0 & w_b \end{bmatrix}$$

$$C=\begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ c_{21} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} \\ c_{31} & c_{32} & c_{33} & c_{34} & c_{35} & c_{36} \\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} & c_{46} \\ c_{51} & c_{52} & c_{53} & c_{54} & c_{55} & c_{56} \\ c_{61} & c_{62} & c_{63} & c_{64} & c_{65} & c_{66} \end{bmatrix}$$

$D = [\mathbf{0}]_{6\times 6}$

where,

$a_{11} = w_b \times r_s \times x_{aq} / x_s{}^2 - w_b \times r_s / x_s$,
$a_{12} = -w$, $a_{13} = 0$,
$a_{14} = w_b \times r_s \times x_{aq} /(x_s \times x_r')$,
$a_{15} = 0$; $a_{16} = 0$

$a_{21} = w$,
$a_{22} = w_b \times r_s \times x_{ad} / x_s{}^2 - w_b \times r_s / x_s$,
$a_{23} = 0$, $a_{24} = 0$,
$a_{25} = w_b \times r_s \times x_{ad} /(x_s \times x_r')$,
$a_{26} = 0$

$a_{31} = 0$, $a_{32} = 0$,
$a_{33} = -r_s \times w_b / x_s$,
$a_{34} = 0$, $a_{35} = 0$, $a_{36} = 0$

$a_{41} = w_b \times r_r' \times x_{aq} /(x_r' \times x_s)$,
$a_{42} = 0$, $a_{43} = 0$,
$a_{44} = w_b \times r_r' \times x_{aq} / x_r'^2 - w_b \times r_r' / x_r'$,
$a_{45} = -(w - w_r)$,
$a_{46} = 0$

$a_{51} = 0$,
$a_{52} = w_b \times r_r' \times x_{ad} /(x_r' \times x_s)$,
$a_{53} = 0$,
$a_{54} = (w - w_r)$,
$a_{55} = w_b \times r_r' \times x_{ad} / x_r'^2 - w_b \times r_r' / x_r'$,
$a_{56} = 0$

$a_{61} = 0$, $a_{62} = 0$, $a_{63} = 0$, $a_{64} = 0$, $a_{65} = 0$,
$a_{66} = -w_b \times r_r' / x_r'$

$c_{11} = 1/ x_s - x_{aq} / x_s{}^2$,
$c_{12} = 0$, $c_{13} = 0$,
$c_{14} = -x_{aq} /(x_s \times x_r')$,
$c_{15} = 0$, $c_{16} = 0$

$c_{21} = 0$,
$c_{22} = 1/ x_s - x_{ad} / x_s{}^2$,
$c_{23} = 0$, $c_{24} = 0$,
$c_{25} = -x_{ad} /(x_s \times x_r')$,
$c_{26} = 0$

$c_{31} = 0$, $c_{32} = 0$,
$c_{33} = 1/ x_s$,
$c_{34} = 0$, $c_{35} = 0$, $c_{36} = 0$

$c_{41} = -x_{aq} /(x_r' \times x_s)$,
$c_{42} = 0$, $c_{43} = 0$,
$c_{44} = 1/ x_r' - x_{aq} / x_r'^2$,
$c_{45} = 0$, $c_{46} = 0$

$c_{51} = 0$,
$c_{52} = -x_{ad} /(x_r' \times x_s)$,
$c_{53} = 0$, $c_{54} = 0$,

$$c_{55} = 1/x'_r - x_{ad}/x_r'^2,$$
$$c_{56} = 0$$

$$c_{61} = 0, c_{62} = 0, c_{63} = 0, c_{64} = 0, c_{65} = 0,$$
$$c_{66} = 1/x'_r$$

VIII. ACKNOWLEDGMENT

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