2004 International Conference on
Power System Technology - POWERCON 2004
Singapore, 21-24 November 2004

A Real-time DSP based quadrilateral relay for distance protection of 25 kV AC traction overhead equipment

U. J. Shenoy, *Member, IEEE,* K. G. Sheshadri, K. Parthasarathy, *Senior Member, IEEE,*
H. P. Khincha, *Senior Member, IEEE*, D. Thukaram, *Senior Member, IEEE*

***Abstract*—This paper presents the design, implementation and testing of a single-phase distance relaying scheme for 25 kV 50 Hz AC traction system using a Texas Instruments TMS320C50 digital signal processor (DSP). The three-phase system with substations, track section with rectifier-fed DC locomotives and a detailed traction load are modeled using Power System Block set (PSB) / SIMULINK software package. The model has been used to study the effect of loading and fault conditions in 25 kV AC traction. The relay characteristic proposed is a combination of two quadrilaterals in the X-R plane in which resistance and reactance reaches are independently controllable. The algorithms, hardware and software are also briefly described.**

***Index Terms*—Traction system, PSB/SIMULINK, Wrong phase coupling, TMS320C50 DSP, Quadrilateral relay characteristic**

I. INTRODUCTION

The function of an AC traction system is to deliver power to the locomotives as efficiently and economically as possible. Problems involved in providing protection to traction systems are different from those faced in protecting other transmission lines or distribution systems working at the same voltage level. This is due to the continuous movement of locomotive load, change in the length of the line during operation, nature of loading, voltage drop due to the flow of the lagging reactive current in inductive components of the overhead system and the high levels of harmonic distortion [1]. The situation is further aggravated due to the use of DC series motors in electric locomotives, which draw large current on starting. It may happen at times that several locomotives run in the same section of the overhead equipment (OHE), leading to large increase in load. The impedance seen by the relay on such heavy loads may be even smaller than that on distant earth faults. Fig. 1 shows the typical feeding arrangement of a 25 kV electrified railway system. The load current drawn by locomotives is rich in large odd harmonic components [2]. The adjacent traction substations are fed from different phases of the three-phase supply in rotation having a phase difference of 120°. The supply to the OHE can be switched ON/OFF through interruptors. Normally power supply from the traction substation extends upto the sectioning post (SP) on either side of the substation, but in case of an emergency necessitating total shut down of the substation, it can be extended upto the failed substation by closing the bridging interruptors at the

U.J.Shenoy, corresponding author (e-mail: ujs@ee.iisc.ernet.in) is Senior Scientific Officer, K.G. Sheshadri (e-mail: kg_sheshadri@yahoo.com) is the Project Assistant, H.P. Khincha (e-mail: hpk@ee.iisc.ernet.in) and D. Thukaram (e-mail: dtram@ee.iisc.ernet.in) are Professors in the Electrical Engg. Department, Indian Institute of Science, Bangalore-560 012.
K. Parthasarathy (e-mail: prdc@vsnl.com) is with the Power Research & Development Company, Bangalore.

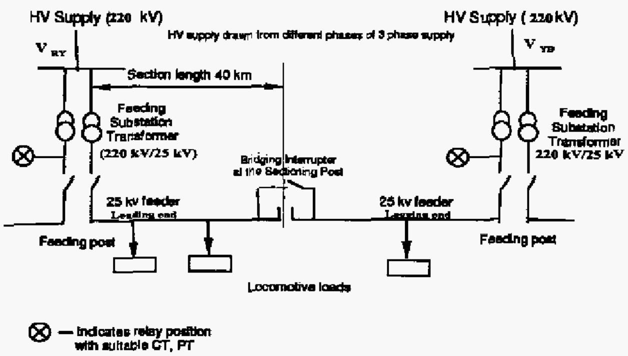

Fig. 1. Typical feeding arrangement of 25 kV traction system of Indian Railways

two SPs. Fault on the OHE can be of two types (i) Earth faults (ii) Phase-to-phase faults. The second fault can occur by accidental closure of the bridging interruptor at the SP during normal feeding condition or by a short circuit at the insulated overlap opposite a traction substation at times of emergency feed conditions. This is termed as Wrong phase coupling (WPC) fault. Under emergency feed conditions, however the zone would extend upto the next traction substation, which is double the normal zone and the relay should provide protection upto the end of next section.

The harmonic currents drawn by the dc motor locomotives degrade the power quality of the traction supply [3]. The excessive voltage drop due to the flow of lagging reactive current makes the performance of the system even worse. Voltage regulation with shunt compensation allows overcoming these drawbacks. Static VAR Compensators (SVCs), Thyristor controlled reactors (TCRs) and Thyristor Switched Capacitors (TSCs) can be used to provide such compensation. However, TCRs are expensive and require additional filters against the harmonic pollution they add into the system in addition to the harmonic load current. TSCs are cheaper devices and do not produce as much harmonic pollution as TCRs. They can provide step changes of the compensation levels from a shunt compensator.

This paper presents the modeling, simulation, implementation and testing of a quadrilateral characteristic single-phase digital distance relay for 25 kV AC traction applications. A Texas Instruments TMS320C50 digital processor (DSP) has been employed to support the high-speed numeric processing capabilities required for high-speed transmission line protection.

II. RAILWAY TRACTION SYSTEM MODEL

In order to investigate the performance of faults and loading conditions, the OHE of a typical 25 kV traction system of the Indian Railways has been considered. The Power System Block set (PSB) of MATLAB/SIMULINK is a modern design tool used to build the simulation models for electric power system as well as its interactions with other systems [4]-[6]. The basic function blocks of the individual subsystems are developed initially and are interconnected to form the full system model. Each system element is modeled based on its specifications [7].

A. Three-phase AC supply system

A three phase 220 kV, 50 Hz AC supply system with the 220 kV single circuit transmission line has been modeled as shown in Fig. 2. The power received from the supply authority grid network is transmitted to the railway's own transmission lines by a series of transformer and line sectioning facilities. The substations have been modeled as subsystems. A bridging interruptor modeled as a switch connected between Substation 1 (Sub1) and Substation 2 (Sub2) facilitates the simulation of WPC faults.

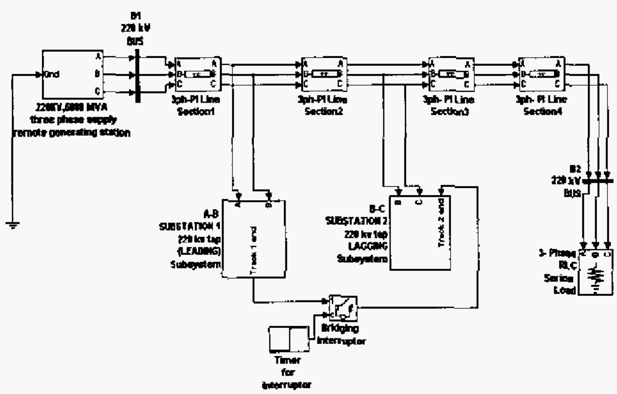

Fig. 2. Model of three-phase supply grid with substations

B. Substation and Track section model

Fig. 3 shows the modeling of Substation 1. The modeling of Substation 2 is identical to that of Substation 1. The 25 kV supply for traction system is drawn through a single phase step down transformer. This is modeled as a 25 MVA, 220 kV/25kV, two winding single phase transformer with impedance of 12% at 25 MVA base. The average length of the catenary to be protected during normal feed conditions is 40 km. This feeder is modeled as ten 4 km pi sections, each having a longitudinal impedance of 0.169+j0.432 Ω/km at 50 Hz and shunt capacitance of 0.011 μF/km [8]. This facilitates the simulation of earth faults from 10% to 90% of the line. In their simplest configuration, the TSCs are constituted of a capacitor bank, where each capacitor may be connected to the system through a thyristor switch and a damping reactor to limit rate of current. The TSC is modeled appropriately by choosing reactor and capacitor values tuned to a particular frequency (i.e. the third harmonic) and can reduce the harmonic pollution.

C. Locomotive model

The locomotives are assumed to be of the conventional thyristor type with a total locomotive rating of 2.5 MW (rated at 25 kV). They are modeled as two half-controlled thyristor-diode bridge rectifiers with each rectifier having parameters of ON state resistance R_{on} = 1mΩ, Forward voltage = 0.8 V, Snubber resistance = 100 Ω as shown in Fig. 4. The upper and lower half-bridge converters convert AC voltage to a controlled DC voltage.

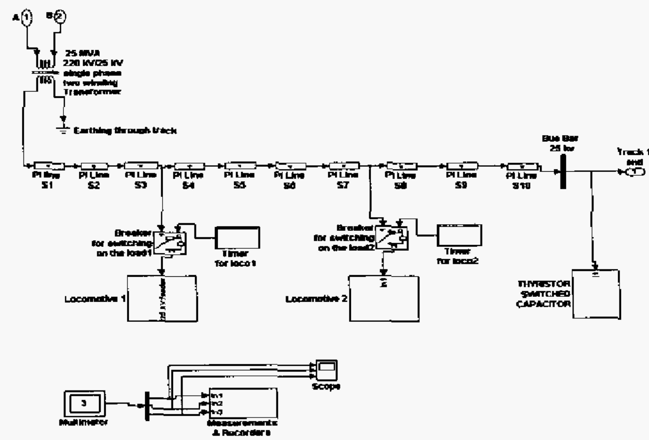

Fig. 3. Model of Substation 1 with 25 kV 40 km traction feeder and loads

AC voltage from the 25 kV feeder is reduced to the required voltage of the power converters. Each thyristor-diode bridge is fed from a 25 kV/ 2 X 400 V three winding single phase transformer having 8% impedance and saturable characteristics. The thyristor converters are used with delayed firing to control the current in lower speed ranges, but for most of the time, the converters operate without any firing delay and speed increase is achieved by field weakening. When two or more locomotives are running together hauling a single train, they are assumed to have identical firing angles. The DC machine motor model in PSB/SIMULINK implements a separately excited machine. The electromechanical torque developed T_e is proportional to the armature current I_a. The parameters chosen are moment of inertia J=0.1 kg.m^2, Initial speed = 10 rad/s, Armature resistance R_a=0.06 Ω, Armature inductance L_a = 0.0012 H.

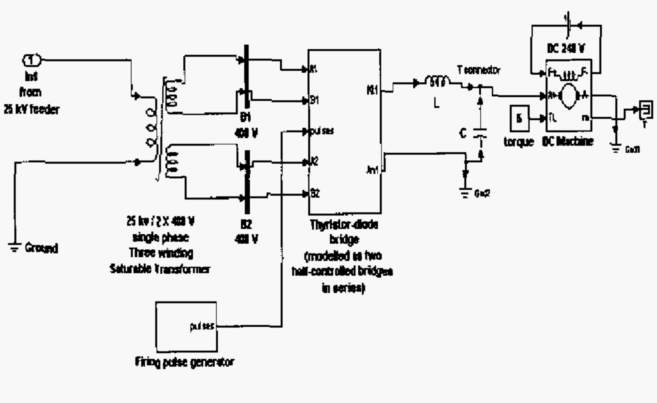

Fig. 4. Model of a single 2.5 MW locomotive

III. SIMULATION RESULTS AND ANALYSIS

In order to investigate the effects of the faults and loading conditions in the traction system, a number of cases have been studied with and without TSC.

A. Simulation waveforms

Figs. 5-7 show some representative simulation waveforms of the feeder voltage and feeder current. The commutation of the locomotive loads generates severe distortion on the track voltage. When four or more locomotives are running, the distortion becomes even worse and also the voltage becomes too low. Initially earth faults were simulated at different points on the traction feeder (from 10% to 90% of the line) with the bridging interruptor open and fault block (modeled as a switch in series with resistance R_F and external timer control) connected. The SIMULINK/PSB also facilitates the timing of the fault by varying the timer parameters, fault resistance and location of the fault. The bridging interruptor was then closed with the earth fault block removed and the WPC simulation studies were carried out. In this case, the waveforms of the feeder voltage, feeder current and load current were monitored at both the leading and lagging end substations as shown in Fig. 6 and Fig. 7.

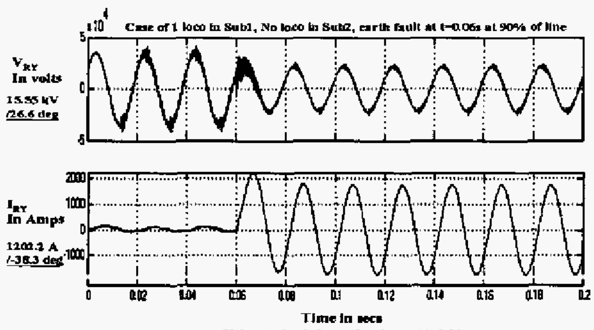

Fig. 5. Waveforms for Case with 1 loco in Sub1, No loco in Sub2, Earth fault at t=0.06 s at 90% of line.

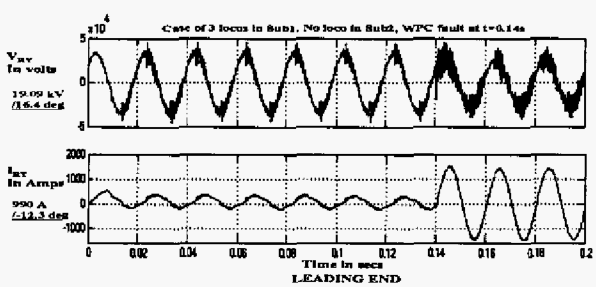

Fig. 6. Waveform for Case with 3 locos in Sub1, No loco in Sub2 (Leading end), WPC fault at t=0.14 s

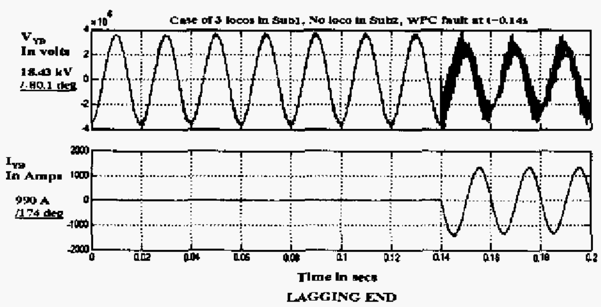

Fig. 7. Waveforms for Case with 3 locos in Sub1, No loco in Sub2 (Lagging end), WPC fault at t=0.14 s

IV. RELAY CHARACTERISTIC

Quadrilateral characteristics have proved very versatile in protecting railway overhead lines. It provides higher resistive coverage than mho characteristic [9]. They permit each relay to protect longer sections of the line, while avoiding the traction load. Heavy traction loading can lead to load encroachment problems. In the proposed digital distance relay, the quadrilateral characteristic is as shown in Fig. 8. The detection of the fault using the above logic applies to Zone-1 protection. The relay reach settings and other parameters have been chosen as given in Table I.

The traction OHE is subjected to frequent earth faults caused by failure of insulation, or by the OHE snapping and touching the earth. These faults are cleared by the feeder circuit breaker. The relay characteristic under normal feed with earth fault conditions is indicated by the first quadrant in the relay characteristic.

Due to overlap of the earth fault and WPC characteristics, some times the earth fault relay operates on WPC fault too. A tripping decision based only on angle is not sufficient enough to detect these fault conditions accurately. The impedance seen by the relay on WPC fault at the substation with lagging voltage always lies in the second quadrant of the relay characteristic while that for earth fault lies in the first quadrant. These two faults can be discriminated by having two relay characteristics as shown in Fig. 8.

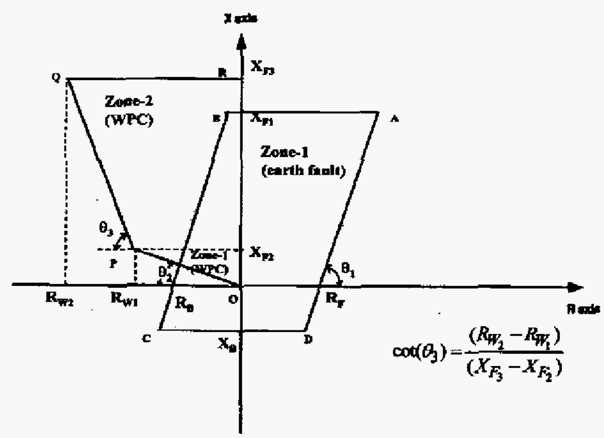

Fig. 8. Quadrilateral relay characteristic for traction feeder

TABLE I
TYPICAL RELAY CHARACTERISTIC PARAMETERS

Parameter	Value setting
Rated Voltage (AC)	110 V
Rated current	5 A
Setting angle θ_1 (Zone-1, Fault)	65 degrees
WPC setting angle θ_2 (Zone-1)	30 degrees
WPC setting angle θ_3 (Zone-2)	64.35 degrees
RELAY REACH SETTINGS	
Forward Resistance reach R_F	8 ∠0 Ω
Forward reactance reach X_{F1}	20 ∠90 Ω
Reverse resistance reach R_B	6 ∠180 Ω
Reverse reactance reach X_B	6 ∠270 Ω
WPC minimum resistance reach R_{W1}	8 ∠180 Ω
WPC maximum resistance reach R_{W2}	20 ∠180 Ω
WPC minimum reactance reach X_{F2}	5 ∠90 Ω
WPC minimum reactance reach X_{F3}	30 ∠90 Ω

A. Calculation of Impedance (R_{cal} and X_{cal})

A Full cycle Fourier relaying algorithm with 12-sample data window has been used to extract the fundamental component from the voltage and current samples. The window is progressively advanced by one sample as new samples of voltages and currents become available. With K=12 samples/cycle, the sine and cosine components of the incoming voltage and current signals (for fundamental frequency f=50 Hz) are determined by the expressions (1) and (2) given below.

$$V_{\sin} = \frac{2}{K}\sum_{n=1}^{K} V_n \sin\theta \quad ; \quad V_{\cos} = \frac{2}{K}\sum_{n=1}^{K} V_n \cos\theta \qquad (1)$$

$$I_{\sin} = \frac{2}{K}\sum_{n=1}^{K} I_n \sin\theta \quad ; \quad I_{\cos} = \frac{2}{K}\sum_{n=1}^{K} I_n \cos\theta \qquad (2)$$

where V_n and I_n are incoming samples of feeder voltage and current. The sine and cosine values are stored in the form of a look-up-table. The values of resistance R_{cal} and reactance X_{cal} are then determined by the equations given in (3) and (4).

$$D.R_{cal} = V_{\sin} \cdot I_{\sin} + V_{\cos} \cdot I_{\cos} \qquad (3)$$

$$D.X_{cal} = V_{\cos} \cdot I_{\sin} - I_{\cos} \cdot V_{\sin} \qquad (4)$$

where $D = I_{sin}^2 + I_{cos}^2$

The 'D' terms have been cross-multiplied in equations (3) and (4) to prevent the need for any digital division algorithm, which could increase the processing burden and delay on the DSP processor [10]. In the logics implemented for the quadrilateral characteristic, the calculated values of resistance and reactance R_{cal} and X_{cal} are compared with the reach settings.

B. Relay Logic

The proposed relay characteristic can be realized by the following equations given in (5), (6) and (7):

For earth fault detection (Zone 1)

$$X_B < X_{cal} < X_{F1} \ AND$$

$$R_B + X_{cal} \cdot \cot\theta_1 < R_{cal} < R_F + X_{cal} \cdot \cot\theta_1 \qquad (5)$$

For WPC detection (Zone 1and Zone 2)

Zone 1: $0 < X_{cal} < X_{F2} \ AND$

$$R_{W1} + X_{cal} \cdot \cot\theta_2 < R_{cal} < 0 \qquad (6)$$

OR

Zone 2: $X_{F2} < X_{cal} < X_{F3} \ AND$

$$R_{W2} + X_{cal} \cdot \cot\theta_3 < R_{cal} < 0 \qquad (7)$$

Additional logic for discriminating between the earth faults and WPC faults has been given in the expression (8)

$$R_{cal} < 0 \quad \text{AND} \quad I_{load} < I_{WPC} < I_{fault} \qquad (8)$$

V. RELAY DESIGN

A. Relay Hardware

Fig. 9 shows the hardware set-up for implementation of the proposed relay consisting of a PC based Waveform simulator, data acquisition system, DSP processor and the host PC system.

PC based Waveform Simulator system

The Waveform playback simulator system consists of a Digital-to-Analog converter (DAC) card that is interfaced to a personal computer (PC) system. The data files containing the samples of the feeder voltage and current obtained from PSB/SIMULINK based simulation studies of traction system are reproduced on real-time basis using the DAC card. A sampling frequency of 60 times the power system frequency (3000Hz for a 50 Hz system) has been used to generate the data for voltage and current signals. The proposed implementation scheme uses a Digital-to-Analog converter card that supports two Burr Brown DAC4815 ICs. Each of the DAC4815 consists of four identical DAC modules having double buffering capability and a voltage output range of +/- 10 V or +/- 5 V [6].

Data Acquisition System

This interface hardware consists of eight identical Analog-to-Digital (ADC) channels. All the eight channels are connected through 8-channel multiplexer. The Burr Brown ADS7804 ADC has been used in the data acquisition system. The ADS7804 ADC is of successive approximation type with a 12-bit resolution, a maximum conversion time of 6 μs and has the capability of latching the converter output until it is read [11]. To achieve simultaneous sampling of all the voltage and current signals, eight S/Hs (LF398- Burr Brown) are used by the ADC. The S/H delay is about 10 μs. The DG508 is an 8-channel single ended CMOS analog multiplexer which connects the output to one of the eight analog inputs depending on the state of a 3-bit binary address that is software controlled. It has a fast access time of 0.2 μs and fast settling time of 0.6 μs. The ADC is interfaced to the Texas Instruments TMS320C50 DSP processor by the Intel Programmable Peripheral interface 8255 chip on the data acquisition board. The desired control signals for ADC channel selection, start-of-conversion, end-of-conversion and read data lines has been programmed through Port-B and Port-C (PC3 and PC7 respectively) of 8255. The bi-directional control signals and data lines between DSP board and data acquisition interface hardware are buffered to ensure minimum loading of the processor.

DSP Hardware

This consists of the Texas Instruments TMS320C50 DSP board interfaced to a front-end MS-DOS PC system, which provides the user interface facility to the DSP board. The DSP processor board implements the relaying scheme by processing the acquired signals obtained from the data acquisition interface board. The TMS320C50 DSP has the following important features such as 40 ns single-cycle fixed-point instruction execution time, single cycle multiply/accumulate (MAC) instructions, 9K X 16-bit single cycle on chip program/data RAM and 16 bit programmable timer [12].

B. Relay Software

The software used in the implementation comprises of Waveform simulator software for signal generation and the relaying software. The user interface software, written in C, runs on the personal computer PC-1 shown in Fig. 9 to which the 12-bit DAC4815 DAC card is interfaced. The user interface software reads the data generation file, which consists of voltages and currents stored in the form of samples and the DAC card converts them into a continuous waveform. The relaying software is written entirely in the Assembly language of the TMS320C50 processor. The relaying software comprises of data acquisition software, data processing software and application software.

The data acquisition software controls the operation of the data acquisition system. The entire data acquisition procedure has been implemented in real-time on Interrupt basis. A 16-bit programmable timer provided in the TMS320C50 board is used to control the sampling of the input signals. The appropriate count value for the required sampling time is loaded into the timer counter that can be used to periodically generate CPU interrupts. The timer operation is controlled by the Timer control register (TCR). Two circular buffers are maintained with appropriate pointers using the auxiliary registers of TMS320C50 to store the incoming samples. The data processing software performs the necessary task of extracting the fundamental components of the voltage and current signals. It implements a 12-sample windowing technique of the Fourier algorithm. The TMS320C50 uses a 16 X 16 bit hardware multiplier that is capable of computing a signed or unsigned 32-bit product in a single machine cycle. The sine and cosine values, stored in the look-up-table are multiplied with incoming signals. The typical MPY/MAC instructions of the DSP perform several operations in a single instruction cycle, thus minimizing the computation timings. The application software implements the relaying algorithms to compute the impedance values (R_{cal} and X_{cal}). The quadrilateral relay characteristic has been realized in software using the suitable relay logic. The relay reach settings and setting angle have been appropriately chosen for a typical 25 kV, 50 Hz single phase AC traction overhead equipment (OHE).

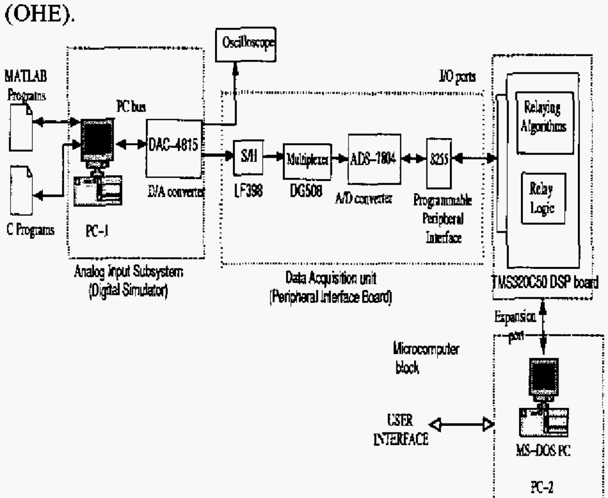

Fig. 9. Block diagram of the hardware set-up for relay characteristic implementation

VI. RESULTS AND DISCUSSION

The performance of the relay has been evaluated using the data simulated from MATLAB/SIMULINK/PSB based studies. The earth fault studies have been carried out for various locations along the traction feeder for different timing of the faults. The performance of the relay for various harmonics in the feeder voltage and current has also been analysed using the Fourier program. For each such case the phase of the feeder voltage and current in both substations and also the impedance seen by the relay at both substation has been tabulated. Table II shows the typical simulated cases. The load distributions have been coded as a number, with each case representing the number of fully loaded locomotives at the related loading points in Fig. 3 both in Substation 1 and Substation 2. For example, a load pattern of 1110 for Substation 1 means that there are 3 locomotives connected to the track section, one at 12 km, the second locomotive at 24 km and the third locomotive at 32 km (as 40 km is modeled as 10 sections). The values of impedance for the simulated cases have been indicated in Table III.

TABLE II
LOAD PATTERN AND FAULT CONDITIONS FOR THE SIMULATED CASES

Case	Substation 1 (loads and TSC)					Substation 2 (loads and TSC)					Earth fault details	WPC Fault details
	L1	L2	L3	L4	TSC	L1	L2	L3	L4	TSC		
1	1	0	0	0	0	0	0	0	0	0	-	-
2	1	0	0	0	0	1	1	0	0	0	-	-
3	1	0	0	0	0	0	0	0	0	0	At t=0.06 s and 90% of line in Sub1 (R_F=0)	-
4	1	1	0	0	0	1	0	0	0	0	At t=0.13s and 80% of line in Sub1 (R_F =5Ω)	-
5	1	0	0	0	0	0	0	0	0	0	-	At t=0.14s
6	1	1	1	0	0	0	0	0	0	0	-	At t=0.14s
7	1	1	1	1	0	0	0	0	0	0	-	-
8	1	1	0	0	0	0	0	0	0	0	-	-
9	1	1	1	1	1	0	0	0	0	0	-	-
10	1	1	0	0	1	0	0	0	0	0	-	-

1 = Connected
0 = Not Connected

TABLE III
TYPICAL VALUES OF IMPEDANCE FOR THE SIMULATED CASES

Case	Substation 1 (Leading end)		Substation 2 (Lagging end)	
	Resistance (R in Ω)	Reactance (X in Ω)	Resistance (R in Ω)	Reactance (X in Ω)
1	81.0	400.0	-	-
2	81.0	403.4	17.2	247.1
3	5.16	11.52	-	-
4	9.46	10.3	7.27	547.8
5	17.4	8.2	-5.94	18
6	16.2	8.7	-5.41	18.1
7	21.2	103.4	-	-
8	37.5	200	-	-
9	21.85	106.6	-	-
10	45.8	212.6	-	-

The feeder voltages and currents have been reproduced using the DAC card after suitable signal conditioning and scaling. The simulated signals are used to evaluate the relay characteristic. For testing, WPC faults, feeder voltage and currents of the lagging end substation have been fed. In this case the relay detects the fault in second quadrant of the characteristic. From Table II and Table III, it is observed that earth fault is detected in first quadrant of relay characteristic. For WPC fault, the relay at the lagging end detects the fault as seen in the second quadrant of the relay characteristic. For example, in Case 4 with load pattern (11000-10000) of 2 locomotives in Sub1, 1 locomotive in Sub2, without TSC and earth fault at t=0.13s at 80% of feeder (in Sub1) line, the values of resistance and reactance are R = 9.46Ω and X = 10.3Ω. The earth fault is detected in first quadrant of relay characteristic. In Case 6 with load pattern (11100-00000) of 3 locomotives in Sub1, no locomotive in Sub2, without TSC and WPC fault at t=0.14s, the values of resistance and reactance at leading end are R = 16.2Ω and X =8.7Ω whereas the corresponding values at lagging end are R = -5.41Ω and X= 18.1Ω. The computations including relay logic are carried out within 120 μs for an inter-sample interval of 1.67 ms (at 600 Hz sampling frequency for the 50 Hz fundamental frequency) using the TMS320C50 DSP hardware scheme.

VII. CONCLUSIONS

This paper describes modeling and simulation of a 25 kV AC traction railway system using MATLAB/PSB. The software supports the accurate modeling and simulation of the traction system. The earth fault and wrong-phase coupling fault are accurately simulated to evaluate the quadrilateral characteristic of single phase distance relaying scheme for traction feeders. The real-time implementation of the above scheme has been developed based on TMS320C50 DSP hardware. The results of simulation studies as well as hardware implementation show that the proposed techniques prove to be accurate tools to develop high-speed and reliable distance relaying scheme for traction applications.

VIII. REFERENCES

[1] R. P. Maheshwari, H. K. Verma, "Adaptive Digital relay for comprehensive distance protection of traction overhead equipment", *Proc. of 6th Intl. Conf. (IEE) on Developments in Power system protection*, Conf. Publication No. 434, 25-27th March 1997, pp. 331-337.

[2] Gao Shibin, He Weijun, Chen Xiaochuan, "Study on microprocessor based adaptive protection relay for heavy duty electric traction system", *Proc. of 6th Intl. Conf.(IEE) on Developments in Power System Protection*, Conf. Publication No. 434, 25th-27th March 1997, pp. 319-322.

[3] G. Celli, F. Pilo, S.B. Tennakoon, "Voltage Regulation on 25 kV AC railway systems by using Thyristor switched capacitor", *Proc. of 9th Intl. Conf.(IEEE) on Harmonics and Quality of Power*, Vol. 2, 1st-4th Oct. 2000, pp. 633-638.

[4] "Power System Blockset User's Guide", Hydro-Quebec, TEQSIM International and The Mathworks Inc., Natick, MA, January 1999.

[5] "Using Simulink", The Mathworks Inc., Natick, MA, January 1999.

[6] "Using MATLAB", The Mathworks Inc., Natick, MA, January 1999.

[7] "Static distance protection relay with parallelogram characteristic for 25 kV AC single phase, 50 Hz traction Overhead equipment", Specification No. ETI/PSI/141 (10/90), Research Designs and Standards organization, Ministry of Railways, Lucknow, India.

[8] Pee-Chin Tan, Robert E. Morrison, Donald Grahame Holmes, "Voltage form factor control and reactive power compensation in a 25 kV Electrified railway system using shunt active filter based on voltage detection", *IEEE Transactions on Industry Applications*, Vol. 39, No. 2, March/April 2003, pp. 575-581.

[9] M.J.Domzalski, K.P.Nickerson, P.R.Rosen, "Application of mho and quadrilateral distance characteristics in power systems", *Proc. of 7th Intl. Conf. (IEE) on Developments in Power System Protection*, Conf. Publication No. 479, 9-12 April 2001, pp. 555-558.

[10] P. J. Moore and A. T. Johns, " Adaptive digital distance protection", in *Proc. of 4th Intl. Conf. (IEE) on Developments in Power protection*, 11th-13th April 1989, pp. 187-191.

[11] "The Burr-Brown IC Data book-Data Conversion Products", Burr Brown Corporation, USA, 1995.

[12] "TMS320C5X User's Guide", Texas Instruments, USA, January 1993.

[13] U. J. Shenoy, B. C. Pal, K. Parthasarathy, A. Pandian, "PC based integrated protection scheme for Railway Traction Applications", *Electrical Machines and Power Systems*, Vol. 23, 1995, pp. 459-467.

[14] L. Hu, R. E. Morrison, D. J. Young, "Reduction of Harmonic distortion and improvement of voltage form factor in compensated railway systems by means of a single arm filter", *Proc. of ICHPS5th Intl. Conf. (IEEE) on Harmonics in Power Systems*, 22nd-25th September, 1992, pp. 83-88.

IX. BIOGRAPHIES

U. J. Shenoy received the B.E. degree in Electronics and Communications from Mysore University in 1979, M.Sc. (Research) in 1986 and Ph.D. degree in 1995 both in Electrical Engineering from the Indian Institute of Science, Bangalore. Since 1984 he has been with Indian Institute of Science as a Scientific staff and presently he is Senior Scientific Officer. He has authored/co-authored more than 30 papers published in national/internal conferences and professional journals. His research interests include DSP and AI applications in power system protection, AC traction systems.

K. G. Sheshadri received the B.E. degree in Electrical Engineering from U.V.C.E College, Bangalore University in 2000. He worked for a private company and joined as a Project Assistant in the Electrical Engineering Department, Indian Institute of Science at Bangalore in 2002. He is currently working in this department as Project Assistant where he has co-authored four papers. His current research interests include digital protective relaying, DSP techniques in power system protection, AI applications to power system protection and analysis of AC traction systems.

K. Parthasarathy received the B.Sc. degree from Mysore University in 1956, the D.I.I.Sc., M.E. and Ph.D degrees in Electrical Engineering from the Indian Institute of Science, Bangalore in 1959, 1961 and 1967 respectively. He was a visiting fellow at the University of Manchester, Institute of Science and Technology, U.K during 1970-71. He has been a faculty and Professor in the Electrical Engineering Department, Indian Institute of Science, Bangalore for over 25 years. He is currently working with Power Research and Development Company, Bangalore as Technical Advisor.

His research interests include computer-aided protection, parallel processing, reactive power optimization and real-time control of power systems.

H.P.Khincha received the B.E. degree in Electrical Engineering from Bangalore University in 1966. He received M.E. degree in 1968 and Ph.D. degree in 1973 both in Electrical Engineering from the Indian Institute of Science, Bangalore. Since 1973 he has been with Indian Institute of Science, Bangalore as faculty where currently he is Professor. His research interests include computer aided power system analysis, power system protection, distribution automation and AI applications in power systems.

D.Thukaram received the B.E. degree in Electrical Engineering from Osmania University, Hyderabad in 1974, M.Tech degree in Integrated Power Systems from Nagpur University in 1976 and Ph.D. degree from Indian Institute of Science, Bangalore in 1986. Since 1976 he has been with Indian Institute of Science as a research fellow and faculty in various positions and currently he is Professor. His research interests include computer aided power system Analysis, reactive power optimization, voltage stability, distribution automation and AI applications in power systems.