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Computer Aided Design of Power Supplies for Rail Transit Systems

J G Yu BSc PhD CEng MIEE

Cegelec Projects Ltd.
(Transportation & Industrial Power Supplies Division)
Boughton Road, Rugby CV21 1BU U.K.

ABSTRACT

The power supply network is a crucial part of the transit system which utilises fixed supplies. Power supply system engineers strive to achieve an optimum between availability, reliability and cost. This process involves a large quantity of calculations, which are needed to predict various combinations of system load conditions under various plant configurations and equipment outage conditions. Such large quantities of calculations can only be dealt with by utilising modern high speed computational methods. This paper describes the development and applications of simulation tools for DC supplied modern transit systems. Particular references are made to the simulator outputs at Cegelec Projects Ltd.

1. INTRODUCTION

In a rail transit system, power supply reliability directly affects the safety of people and plant. Also, the quality of power supply influences the quality of passenger services. Therefore, power supply systems must be designed to have sufficient capacities and ratings to deliver the power required to operate the rail network, under the worst conditions specified. On the other hand, over design should be avoided and the least possible cost should be incurred.

In a transit system, the dynamic interaction between a motion subsystem and an electric power subsystem involving both time and space variables must be studied in order to predict power demand on the supply system. As trains move along the tracks, train positions change and the modes of operation change (motoring, coasting, braking either with or without regeneration, dwelling). Subsequently power demands change and the power network parameters (voltages and currents) change according to demands. On the other hand, supply is not unlimited. It can be a restraint on the demand. In this case demand must be reduced. For transit systems that utilise regenerative braking, if the regenerative energy cannot be absorbed completely by other trains, the regenerating trains must reduce outputs to the system (assuming other receptive devices are not fitted in the system). All this makes the simulation a necessarily iterative process.

In order to achieve an optimum design, a large quantity of calculations are needed. These calculations are used to predict system performances and equipment ratings under various combinations of system load conditions, plant configurations and equipment outage conditions. Such large quantities of calculations can only be dealt with efficiently and speedily by utilising modern high speed computional methods.

In the following sections, the applications of simulation tools for DC powered modern transit systems are described. Particular references are made to outputs generated by the simulator used by Cegelec Projects Ltd.

2. SYSTEM SIMULATION

Traction system simulation techniques have been widely used in the last two decades [1,2,3]. These are being continuously developed to suit the needs of individual projects. Previously these were limited to modelling DC traction motors only. With the rapidly increasing applications of AC traction motors, new techniques have been developed to study traction power networks that feed either DC or AC traction motors, or both [6].

For simplicity in discussion, only DC powered transit systems are considered in this paper. AC supplied power systems are different in details but are similar in principles.

The interaction between the motion subsystem and the power subsystem is via the traction motors. The motoring dynamics and energy requirement can be described via four sets of motor characteristics. These are:

- tractive efforts vs. train speed in motoring mode;
- power demands vs. train speed in motoring mode;
- braking efforts vs. train speed in regeneratively braking mode;
- power feedbacks vs. train speed in regeneratively braking mode.

The motor characteristics are given at certain speed intervals (typically at 1 km/h) and tabulated as look-up tables. These tables are then accessed by the multi-train simulator and stored in designated arrays. For a train moving at a specific speed and under a specific DC voltage (parameters which are derived from simulation), the actual electric model can be established using this data by way of linear interpolation.

A different traction motor, or the same motor under a different control strategy, produces a different set of characteristics. All these are taken into account as data inputs.

3. SYSTEM PERFORMANCES

System performances are then summarised in tables and plotted graphically for the specified operating condition. The following sections describe in detail the summaries for a typical double track (18km), 1500V DC supplied rail transit system, utilising AC induction motors drives.

3.1 TRAIN VOLTAGES

The following output from the simulator gives a panoramic view of the system performance.

```
       Overall System Summaries
--------------------------------------------------
 Parameters                    Uproad    Downroad
--------------------------------------------------
 Mean no. of units on road     15.6      15.5
 Average motoring voltage (V)  1439.     1439.
 Average braking voltage  (V)  1597.     1599.

 Min. train voltage       (V)  1250.     1270.
       occurring at       (m) 15236.     2019.
 drawing a current of     (A)  2872.     3052.

 Max. train voltage       (V)  1700.     1700.
       occurring at       (m) 17488.    14042.
 drawing a current of     (A) -2230.    -2279.

 Min. train current       (A) -2305.    -2307.
       occurring at       (m)  3647.    14060.
       train voltage      (V)  1672.     1684.

 Max. train current       (A)  3066.     3068.
       occurring at       (m)  5316.    12920.
       train voltage      (V)  1366.     1346.
--------------------------------------------------
Occurrences of motoring tapers (both roads):  0
Occurrences of braking  tapers (both roads):  0
```

For example, the minimum train voltage is evaluated in order to assess the system performances. If the voltage falls below certain values, the system needs to be improved. Motoring taper indicates the extent of reduced performance due to low voltage and regenerative taper indicates the extent of non-receptivity due to high voltage.

3.2 INTER-STATION SUMMARIES

In the next step, the inter-station running of a typical train is assessed in detail. The following output from the simulator is obtained.

```
             Typical Train Inter-Station Running Results
.........................................................................
   From         To          | Section   Run   Avrg   Avrg   Av.Mot   Min.
  station      station      | Length   Time   Speed  Volt    Volt    Volt
.........................................................................
 1 STOP-1      STOP-2       |   1550.    99.    56.  1530.  1478.  1410.
 2 STOP-2      STOP-3       |    950.    72.    47.  1487.  1326.  1252.
 3 STOP-3      STOP-4       |   1310.    90.    52.  1470.  1361.  1286.
 4 STOP-4      STOP-5       |   1360.    94.    52.  1511.  1442.  1384.
 5 STOP-5      STOP-6       |    930.    70.    48.  1487.  1419.  1349.
 6 STOP-6      STOP-7       |   1100.    79.    50.  1531.  1493.  1432.
 7 STOP-7      STOP-8       |    910.    67.    49.  1532.  1479.  1438.
 8 STOP-8      STOP-9       |    910.    67.    49.  1527.  1472.  1426.
 9 STOP-9      STOP-10      |   1210.    81.    54.  1548.  1505.  1480.
10 STOP-10     STOP-11      |   1010.    71.    51.  1557.  1501.  1450.
11 STOP-11     STOP-12      |   1070.    75.    51.  1567.  1496.  1466.
12 STOP-12     STOP-13      |   1440.    93.    56.  1514.  1414.  1333.
13 STOP-13     STOP-14      |   1330.    87.    55.  1514.  1438.  1376.
14 STOP-14     STOP-15      |    960.    73.    47.  1447.  1339.  1252.
15 STOP-15     STOP-16      |   1580.    98.    58.  1481.  1419.  1326.
.........................................................................
            Sums            |  17620.  1216.
            Averages        |                   52.  1513.  1439.
            Minimum         |                   47.  1447.  1326.  1252.
.........................................................................
 Total dwell time [excl. 2 ends] =  420.0
 Total run time incl. dwell time = 1636.0
 Commercial speed =   38.8 km/h
```

3.3 RAIL POTENTIAL AND STRAY CURRENTS

In transit systems where the running rails are used as traction current return conductors, rail potential and stray currents are two important parameters. The maximum potential is utilised to evaluate touch voltages. Studies on touch voltages and stray currents in traction systems are described in [4,5].

When trains move along the tracks, rail potential profiles change. Snapshots at two different instants are taken and shown in figures 1 and 2. These indicate that maximum potential occurs at different locations at different times. The maximum and minimum potentials vs. time are shown in figure 3 with total stray current vs. time shown in figure 4.

An integration of the total stray current over the period of time gives the gross leakage charge. For example, in figure 4, the gross leakage charge in 240 seconds is 6583 Coulombs.

This parameter is used as an indicator for electrolytic corrosion by traction generated stray currents. For example, different earthing strategies (floating system, directly grounded system or diode grounded system, etc), or different levels of track insulation, result in different gross leakage charges (and touch voltages). These can be studied to determine the touch voltage and stray current control strategies.

3.4 AC SIDE HARMONICS AND VOLTAGE DISTORTIONS

Due to the use of nonlinear devices in traction systems, harmonics are generated by the loads, which affects the quality of supply in the AC system.

DC loads are obtained for each substation from the simulation, which are then referred to the AC side to study the AC systems, e.g. load flows, harmonic currents and voltage distortions. Load flows can be studied by using commercial software packages. The following output from the simulator summarises the AC system parameters.

```
Reference Frame:   10.0KV   - Secondary Side of PCC Transformer
--------------------------------------------------------------------------
                                |  Point of Common Coupling ID
  Parameters                    |    PCC1    PCC2
--------------------------------------------------------------------------
  Power Delivered:        Peak  |   40.22   34.77
  by PCC (MVA)            Mean  |   20.09   14.18
                          Min   |    4.13     .00
--------------------------------------------------------------------------
  Fundamental:            Peak  |   2322.   2007.
  Current (A)             RMS   |   1316.   1044.
--------------------------------------------------------------------------
  11th Harmonic:          Peak  |   87.01   68.00
  Current (A)             RMS   |   60.58   46.22
--------------------------------------------------------------------------
  13th Harmonic:          Peak  |   55.22   41.89
  Current (A)             RMS   |   40.98   30.90
--------------------------------------------------------------------------
  Total Voltage:          Peak  |   10.12    7.83
  Distortion (%)          Mean  |    6.76    4.73
--------------------------------------------------------------------------
  Busbar Voltage:         Mean  |   96.84   97.79
  (% of Nominal)          Min   |   91.99   92.93
--------------------------------------------------------------------------
  Power Factor:           Mean  |    .967    .974
  (p.u.)                  Min   |    .943    .935
--------------------------------------------------------------------------
```

These values are then checked against customer specification, which is usually based on the recommendations in G5/3 in the U.K. [8]

4. EQUIPMENT RATINGS

The DC traction system incorporates a variety of equipments or plants, which must be adequately rated in order to provide reliable supplies. The following sections describe how these ratings are allocated.

4.1 TRANSFORMER AND RECTIFIER RATINGS

The rectifiers and transformers are rated according to predicted loadings under specified conditions. Load cycles are plotted in graphical forms. Typical current and voltage plots for the rectifiers in substation TSS3 are shown in figures 5 and 6. These are supplemented by numerical summaries. The following numerical output gives a list of predicted load in each traction substation.

```
       Summary for Rectifier Loads/Currents over  240 updates
---------------------------------------------------------------------
      Name of      |  AVG   MAX.    AVG    MIN.   AVG    RMS    PEAK
      Subs/TPH     |  MW    VOLTS  VOLTS  VOLTS    KA     KA     KA
---------------------------------------------------------------------
 2 TSS-1           | 4.41   1696   1535   1441    2.96   3.87   7.47
 3 TSS-2           | 5.68   1687   1522   1393    3.90   5.13   9.86
 4 TSS-3           | 4.57   1669   1532   1460    3.03   3.59   6.55
 5 TSS-4           | 4.13   1601   1538   1495    2.71   3.00   4.80
 6 TSS-5           | 4.02   1649   1541   1467    2.66   3.19   6.23
 7 TSS-6           | 5.22   1695   1528   1384    3.56   4.79  10.31
 8 TSS-7           | 4.00   1687   1542   1451    2.67   3.55   6.98
---------------------------------------------------------------------
Total system mean loading: 32.04 MW
Total Network mean losses:  1.29 MW   or: 4.0 % of system loading
```

The RMS current in the rectifier is a good indicator for long term loading. A load/capacity ratio can be derived to indicate whether the capacities are sufficient. Such ratios are useful to check against specified requirement, e.g., those based on BS4417 in the U.K. [7]

Due to the fluctuation of loads, the exact load cycles for each substation need to be known in order to check short term loads. These are plotted in graphical forms. The following numerical output gives an indication of such load cycles.

```
Occurrence of Rectifier Over-Currents (seconds) over a 100 second load cycle
---------------------------------------------------------------------------
No.      Name of   |  Rated        Percentage of Ratings
        substation |  Curr.      100%     150%     300%
---------------------------------------------------------------------------
 2 TSS-1           |   4600.     31.7     10.8       .0
 3 TSS-2           |   4600.     40.4     32.5       .0
 4 TSS-3           |   4600.     30.8       .0       .0
 5 TSS-4           |   4600.      2.9       .0       .0
 6 TSS-5           |   4600.     17.9       .0       .0
 7 TSS-6           |   4600.     32.5     21.7       .0
 8 TSS-7           |   4600.     31.3       .4       .0
---------------------------------------------------------------------------
```

This information is used to design the transformer/rectifier units. A typical graphical output from the transformer and rectifier design program is shown in figure 9.

4.2 DC SWITCHGEAR RATINGS

DC track feeder currents are used to determine the continuous ratings of DC switchgear and track feeder cables. Load cycles are plotted in graphical forms. A typical load cycle plot for feeder 1 of TSS3 is shown in figure 7. The following numerical summary from the simulator is obtained.

```
                    RMS Currents of Feeders (KA):
----------------------------------------------------------------------
ID  Sub/TPH Name    |    F-1    F-2    F-3    F-4  |  "F-5"  "F-6"
----------------------------------------------------------------------
 2  TSS-1           |    .24   2.26    .24   1.75  |   2.43   1.90
 3  TSS-2           |   1.45   1.45   2.23    .76  |   2.71   2.69
 4  TSS-3           |   1.56   1.84   1.99   1.57  |   2.31   2.50
 5  TSS-4           |   1.18   1.44   1.56   1.22  |   1.75   1.67
 6  TSS-5           |   1.18   1.92   1.60   1.37  |   2.17   2.02
 7  TSS-6           |    .66   1.94   1.44   1.23  |   2.39   2.51
 8  TSS-7           |   1.67    .00   2.25    .00  |   1.67   2.25
----------------------------------------------------------------------
   Maximum Currents |   1.67   2.26   2.25   1.75  |   2.71   2.69
----------------------------------------------------------------------
Note:  "F5"=F1+F2 (total uproad);  "F6"=F3+F4 (total downroad)
```

Peak currents are used to check short term loadings. This information is contained in the following output.

```
                    Peak Currents of Feeders (KA)
----------------------------------------------------------------------
ID  Sub/TPH Name    |    F-1    F-2    F-3    F-4  |  "F-5"  "F-6"
----------------------------------------------------------------------
 2  TSS-1           |    .72   4.68    .46   3.14  |   4.93   3.39
 3  TSS-2           |   2.92   3.57   5.13   2.54  |   5.22   5.74
 4  TSS-3           |   3.06   3.88   4.21   2.98  |   4.52   4.57
 5  TSS-4           |   2.58   3.41   3.66   2.43  |   3.36   3.12
 6  TSS-5           |   2.64   4.21   3.36   2.63  |   3.68   3.98
 7  TSS-6           |   1.72   4.83   3.68   2.56  |   5.56   5.17
 8  TSS-7           |   2.98    .00   5.22    .00  |   2.98   5.22
----------------------------------------------------------------------
```

Peak currents are also used to check instantaneous settings for DC protection.

In addition to the continuous ratings, the switchgear must have adequate short circuit breaking capability. This is determined by DC system fault calculations, of which local rectifier fault current is an important parameter. This is shown in figure 9.

4.3 DC CABLE RATINGS

The DC feeder cables share the same currents with the corresponding DC switchgear. The RMS currents are used to determine continuous ratings. The short term loadings are also an important factor in deciding whether the cable has sufficient thermal capacities. The following summary is generated by the simulator for this purpose.

```
Continuous Feeder Currents above Certain Thresholds (seconds)
-------------------------------------------------------------
TSS NAME           AMPS |    F-1   F-2   F-3   F-4
-------------------------------------------------------------
TSS-3               500 |    64    74    62    79
                    750 |    60    71    61    50
                   1000 |    57    62    59    49
                   1250 |    43    45    58    48
                   1500 |    42    40    55    27
                   1750 |    41    38    52    17
                   2000 |    24    33    46    12
                   2250 |    10    27    43    10
                   2500 |     8    21    28    10
                   2750 |     3    18    21    10
                   3000 |     1    15    15     0
                   3500 |     0     9     5     0
                   4000 |     0     0     2     0
                   4500 |     0     0     0     0
-------------------------------------------------------------
```

The feeder cable duty for feeder number 1 is shown in figure 8. This output also can be used to check the relay settings for cable overload protection (e.g., inverse time over-current protection).

4.4 POWER CONDUCTOR RATINGS

Power conductors, whether in a third rail system (and a fourth rail in some systems) or in an overhead systems of catenary and contact wires, need to be rated adequately to carry the predicted currents. The following output is for such purposes.

```
     Power Conductor Current (RMS, kA)
---------------------------------------------
Sections No. 3  between TSS-2      and TSS-3
TotNo.  No.  EndPosn(m) UpRd(A) DnRd(A)
---------------------------------------------
   79    1       50    1400.1     762.9
   80    2      100    1229.7     760.3
   81    3      150    1092.9     739.3
   82    4      200    1004.8     666.6
   83    5      250     931.7     630.7
   84    6      300     873.0     607.0
   :     :       :        :         :
  119   41     2040    1482.9    1347.0
  120   42     2090    1492.1    1410.7
  121   43     2140    1496.6    1484.2
  122   44     2190    1506.8    1570.2
  123   45     2240    1555.5    1680.4
  124   46     2290    1580.4    1850.7
---------------------------------------------
```

Graphical plots for the whole system are obtainable. This is supplemented by the maximum values in each feeding section as given in the following output.

```
      Maximum Values between Feeding Sections
............................................................
Section   Section  |      UPROAD       |     DOWNROAD
Starting  Ending   |    Max      Posn  |     Max      Posn
  at       at      |  Curr(KA)   (km)  |   Curr(KA)   (km)
............................................................
EOL-1 T    TSS-1   |     .002     .040 |     .002     .040
TSS-1      TSS-2   |    2.182     .130 |    2.103    3.890
TSS-2      TSS-3   |    1.580    6.180 |    1.851    6.180
TSS-3      TSS-4   |    1.729    6.230 |    1.548    6.230
TSS-4      TSS-5   |    1.330    9.150 |    1.457   11.320
TSS-5      TSS-6   |    1.817   11.370 |    1.363   13.830
TSS-6      TSS-7   |    1.813   13.880 |    1.915   17.700
TSS-7      EOL-2 T |     .000     .000 |     .000     .000
............................................................
Grand Max. Value   |    2.182          |    2.103
............................................................
```

5. SUMMARY

The applications of computer simulation techniques to rail transit power system design are described. Simulator outputs are formulated according to project engineering need. These are used to evaluate system performances and rate equipments.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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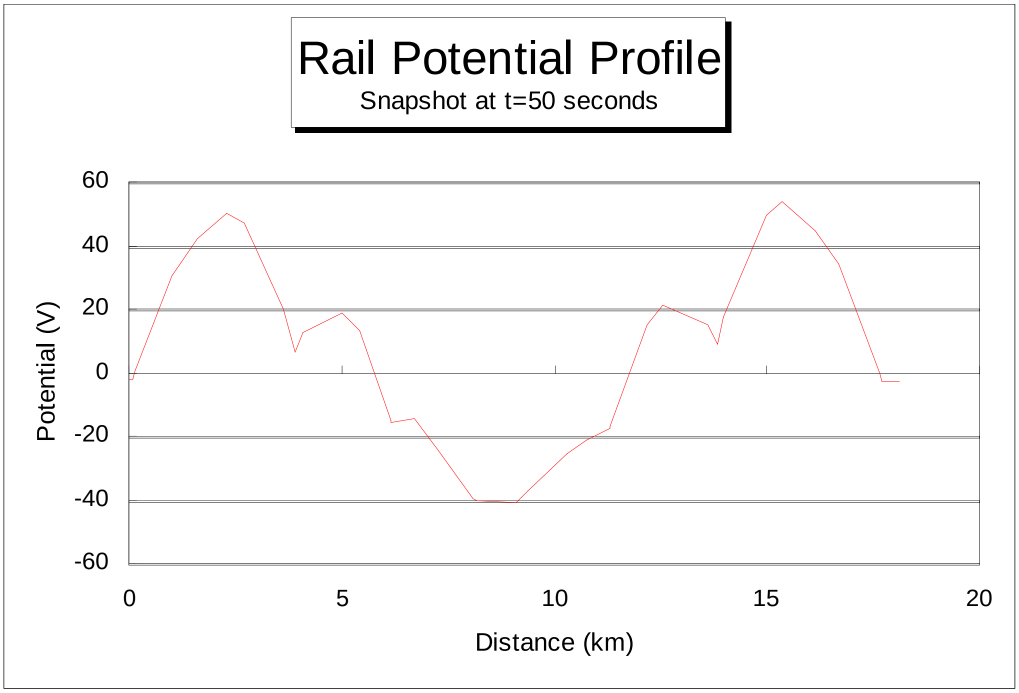


Figure 1

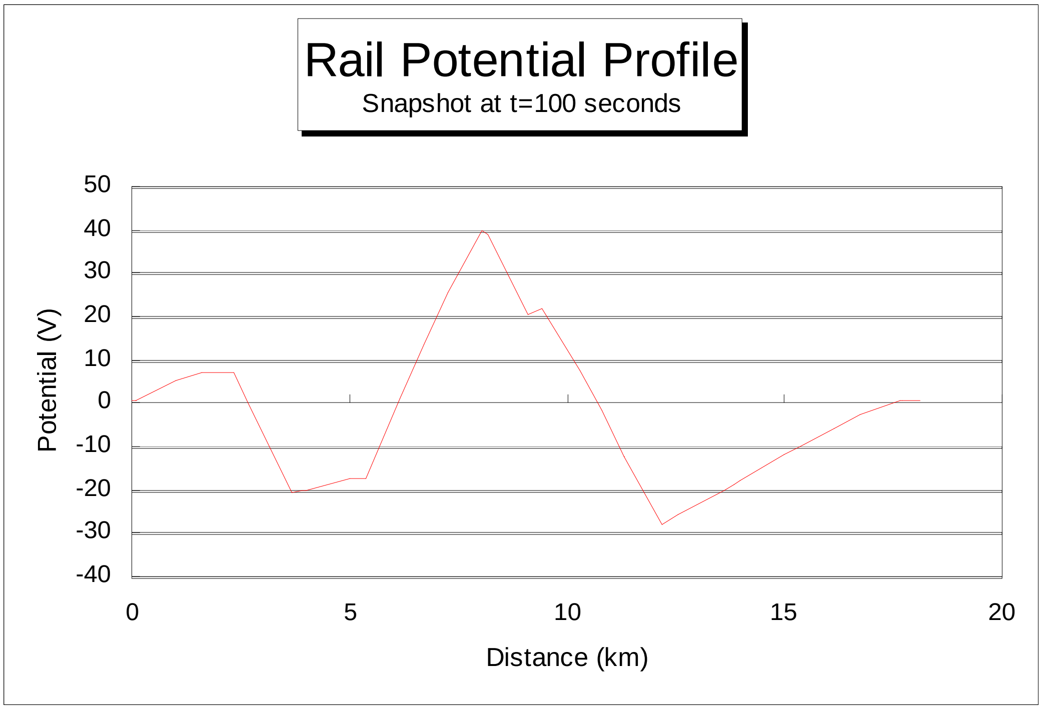


Figure 2

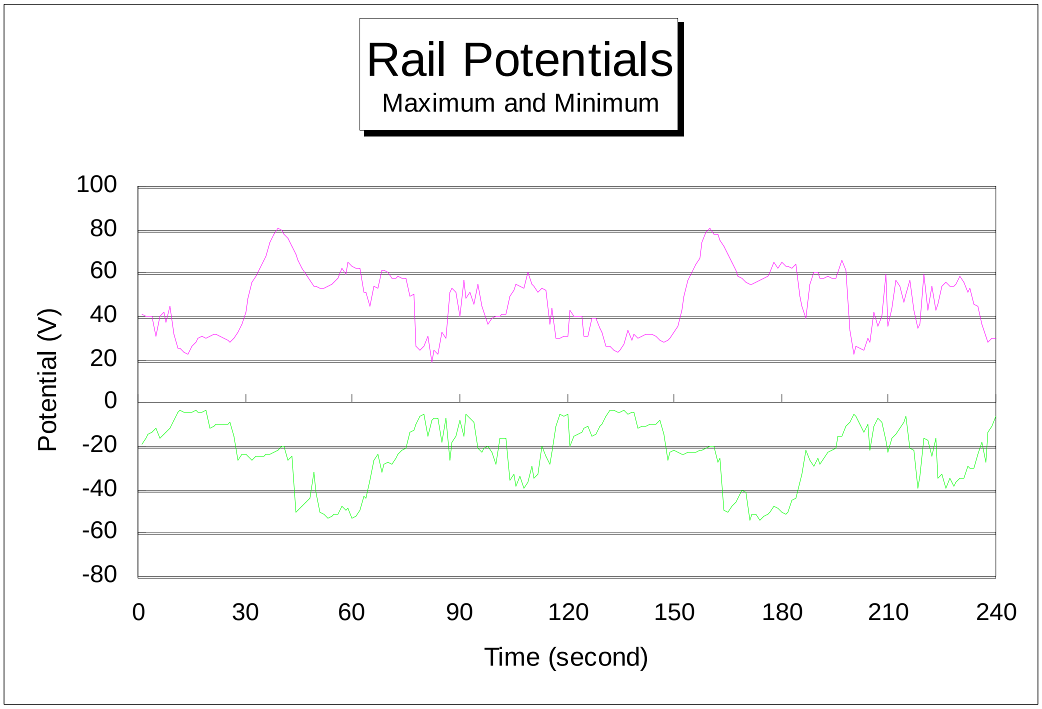


Figure 3

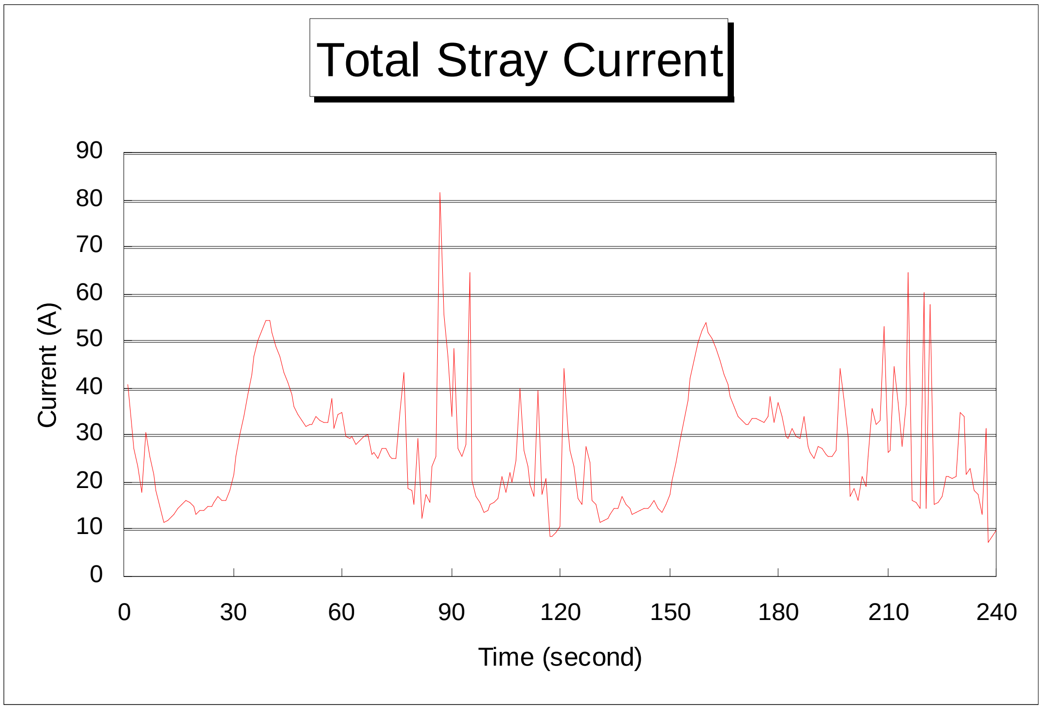


Figure 4

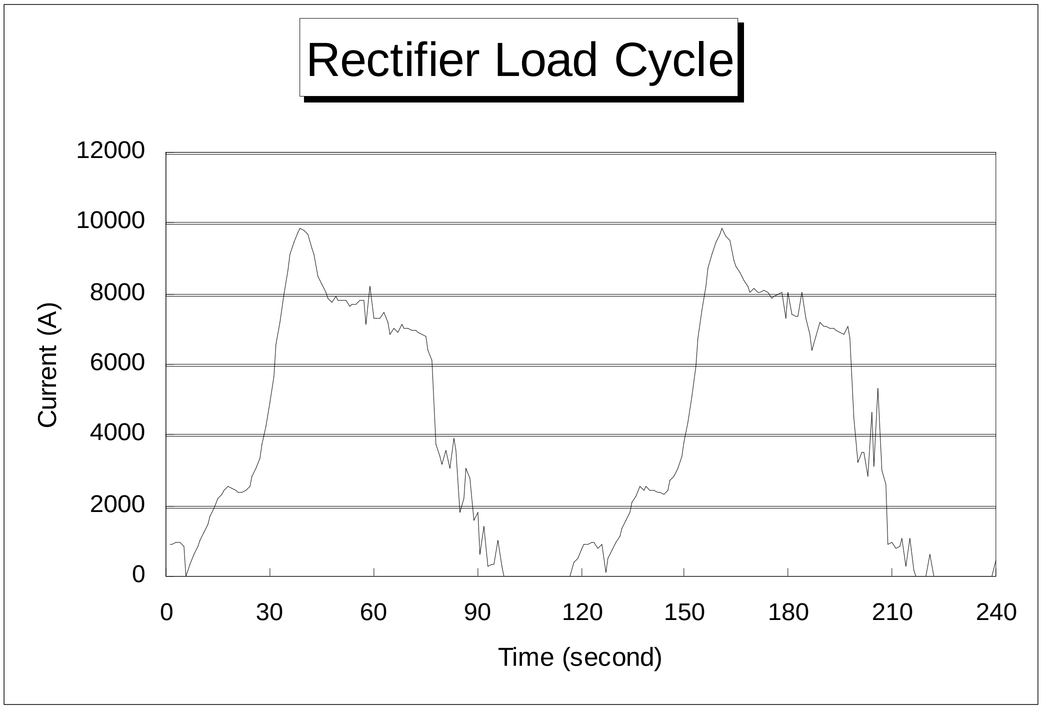


Figure 5

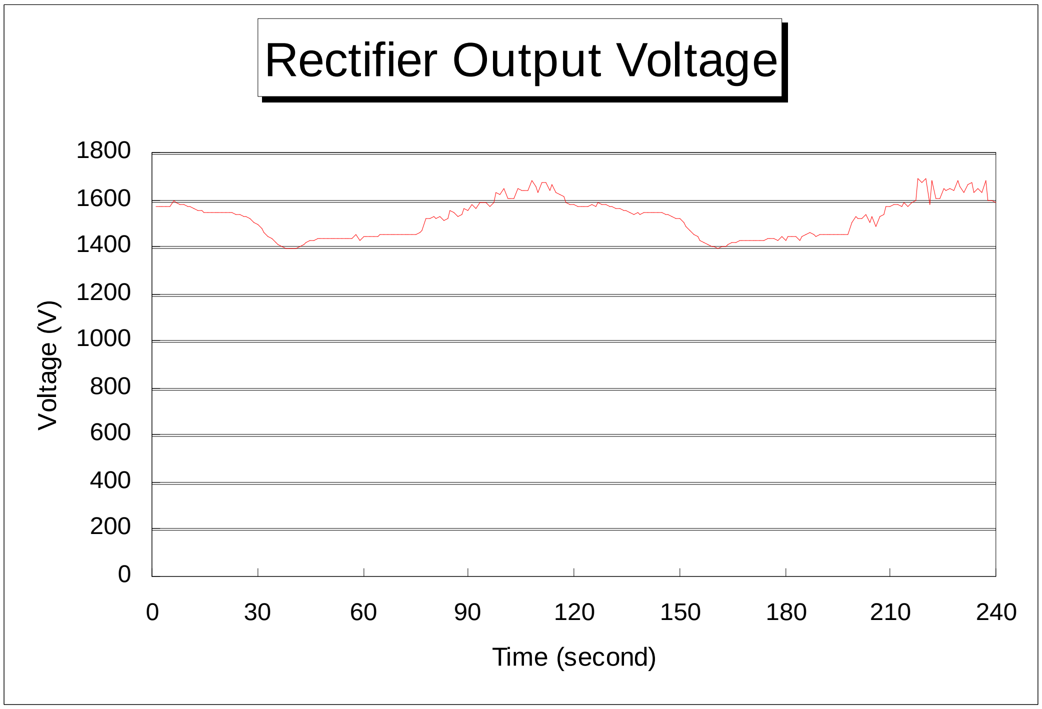


Figure 6

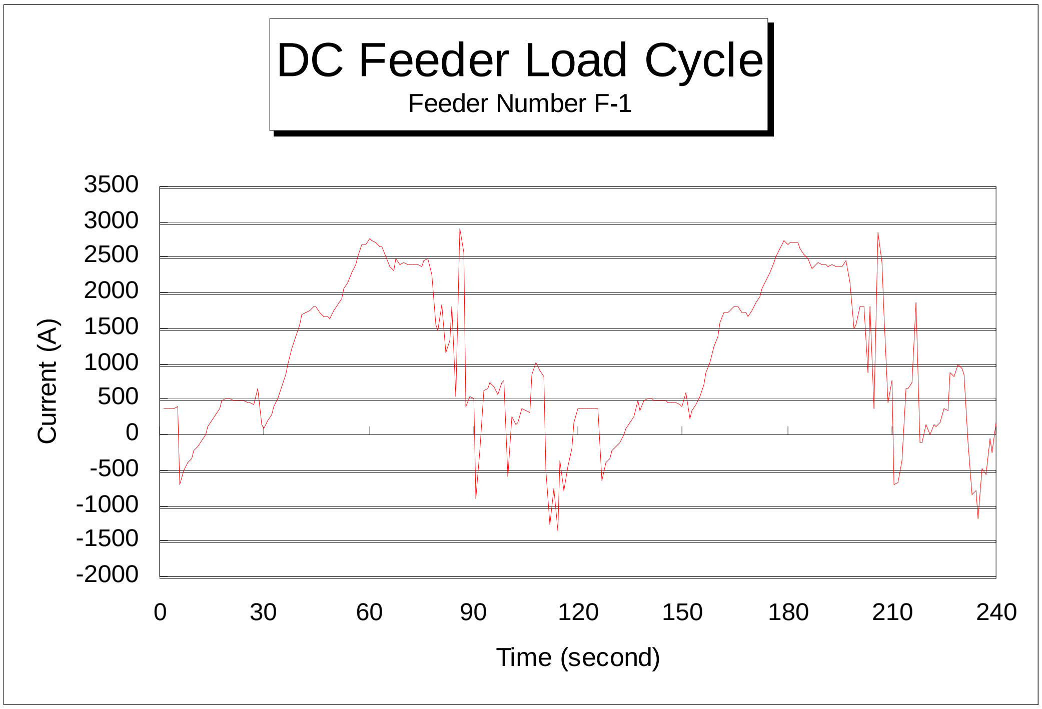


Figure 7

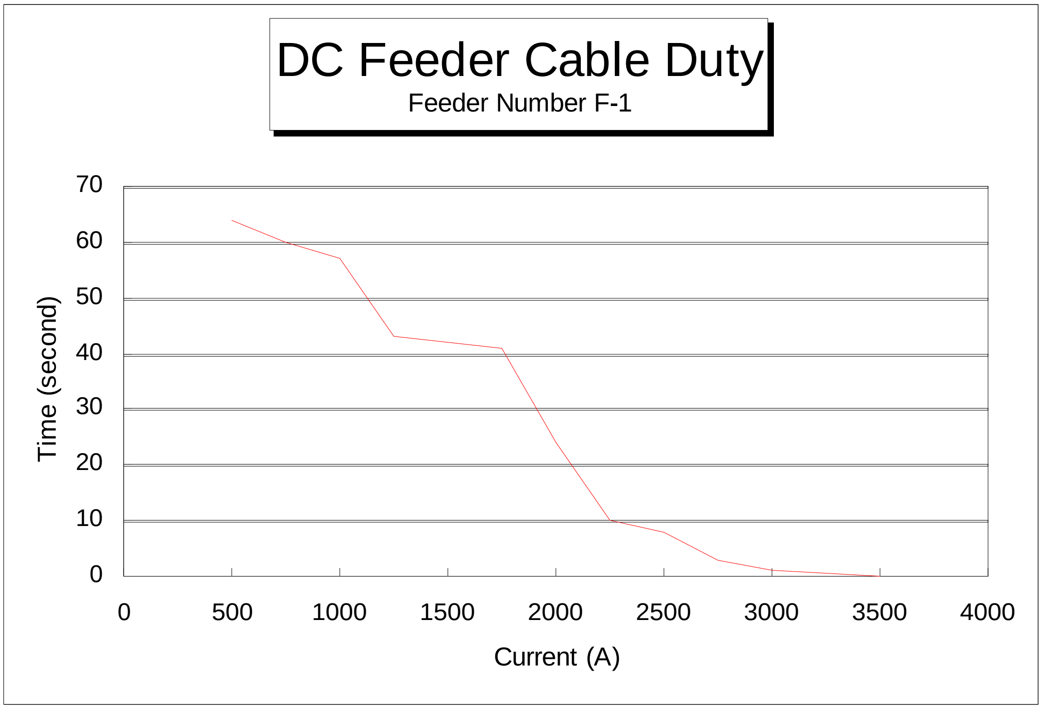
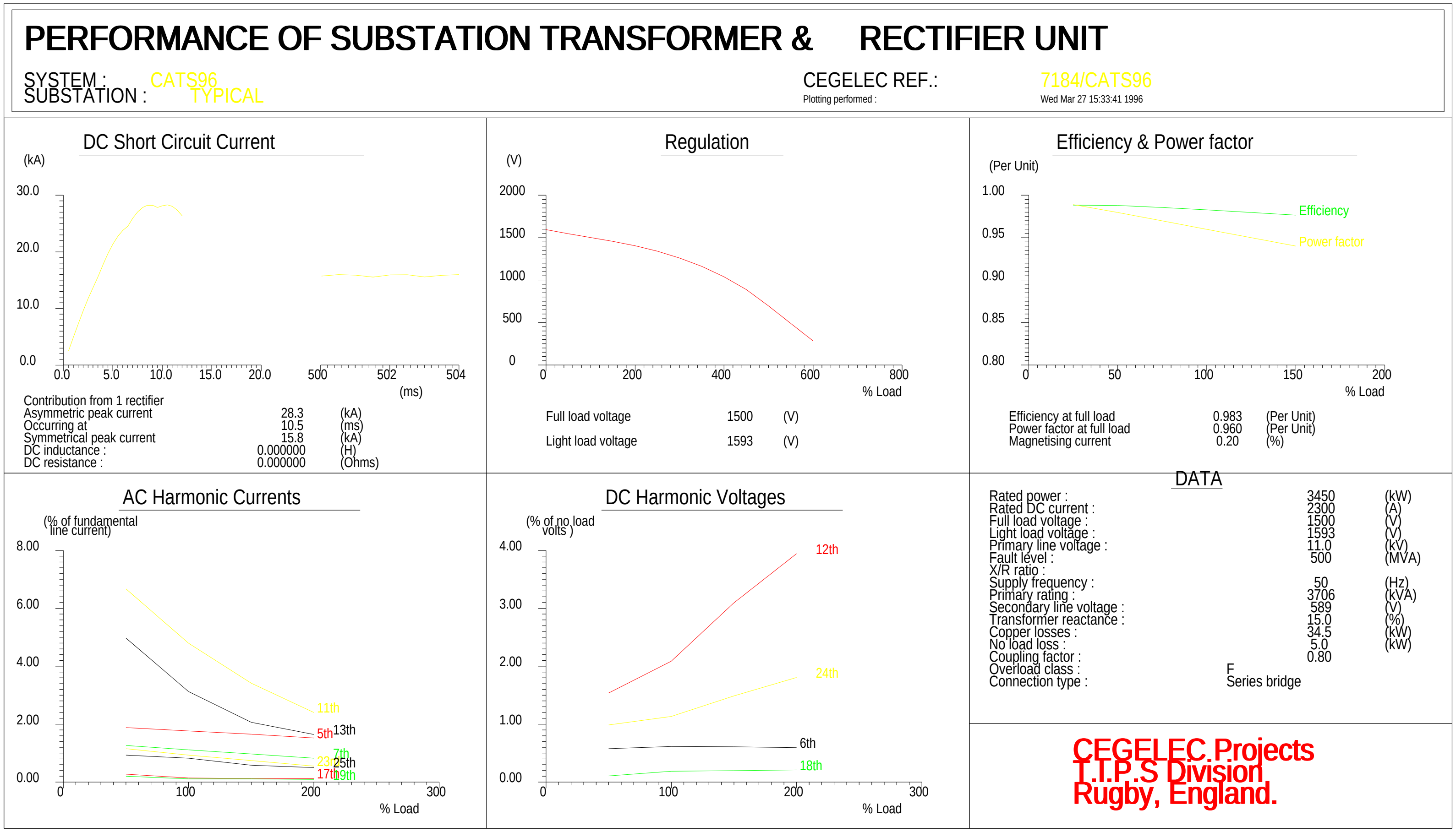


Figure 8



PERFORMANCE OF SUBSTATION TRANSFORMER & RECTIFIER UNIT

SYSTEM : CATS96
SUBSTATION : TYPICAL
CEGELEC REF.: 7184/CATS96
Plotting performed : Wed Mar 27 15:33:41 1996

Contribution from 1 rectifier

Asymmetric peak current	28.3	(kA)
Occurring at	10.5	(ms)
Symmetrical peak current	15.8	(kA)
DC inductance :	0.000000	(H)
DC resistance :	0.000000	(Ohms)

Full load voltage	1500	(V)
Light load voltage	1593	(V)

Efficiency at full load	0.983	(Per Unit)
Power factor at full load	0.960	(Per Unit)
Magnetising current	0.20	(%)

DATA

Rated power :	3450	(kW)
Rated DC current :	2300	(A)
Full load voltage :	1500	(V)
Light load voltage :	1593	(V)
Primary line voltage :	11.0	(kV)
Fault level :	500	(MVA)
X/R ratio :		
Supply frequency :	50	(Hz)
Primary rating :	3706	(kVA)
Secondary line voltage :	589	(V)
Transformer reactance :	15.0	(%)
Copper losses :	34.5	(kW)
No load loss :	5.0	(kW)
Coupling factor :	0.80	
Overload class :	F	
Connection type :	Series bridge	

CEGELEC Projects
T.I.P.S Division
Rugby, England.

Figure 9