OPTIMIZED ALGORITHMS FOR EFFECTIVE DRIVING OF TAP CHANGER CONTROLLED ELECTRIC LOCOMOTIVES IN INDIAN RAILWAYS : A CASE STUDY

Shayak Bhattacharjee

Department of Physics, Indian Institute of Technology Kanpur, NH-91, Kalyanpur, Kanpur – 208016, Uttar Pradesh. email : shayak@iitk.ac.in , shayak12424@yahoo.in

* * * * *

Keywords : Tap changer locomotive, WAP4, dc traction motor, notch, shunt

Abstract

In this work we propose a strategy for driving a tap changer controlled electric locomotive, specifically WAP4, which will result in the highest possible output performance while remaining within the tolerance limits of the voltage and current in the traction motors.

* * * * *

Acknowledgement

I would like to express my heartfelt thanks to Shri Bhawnath Jha, loco pilot (Rajdhani) of ALD Division, NCR for painstakingly collecting dozens of run time data sets which I have used in this Article. Without his contribution, the calculations presented here would have been impossible and I remain forever grateful to him.

* * * * *

1. Introduction

Indian Railways' electric locomotive fleet [1] is today dominated by tap changer controlled, or 'conventional' machines. In the passenger area, the indigenously designed and manufactured WAP4 is the mainstay of electric traction with over seven hundred units in active service. Certain fast and prestigious trains, such as NDLS-DBRT, NDLS-RNC* and NDLS-BBS Rajdhani Express, NDLS-HWH, NDLS-SDAH* and HWH-CSTM Duronto Express are regularly hauled by WAP4s (a list of relevant station codes is given in Appendix 1). Another challenging load category, which is the tightly scheduled superfast with 22 to 24 self-generating coaches, is handled in bulk by these locomotives. A few examples of such heavy superfasts with WAP4 as regular link are HWH-JU Express, NDLS-TVC Kerala Express, HWH-CSTM Gitanjali Express, HWH-MAS Coromandel Express and LJN-CSTM Pushpak Express. With a continuous output of 5000 horsepower (HP) and a maximum well above that, and a peak tractive effort (TE) upwards of 300 kN, WAP4 is more than adequate for any train haulage task in Indian Railways (IR) at the present time.

The primary competitors of WAP4 are the imported and imported-modified locomotives WAP5 and WAP7 which are powered by electronically controlled three-phase induction motors. These locos offer three significant benefits over WAP4, of which one is infrastructural, one operational and one ergonomic. The first is that the squirrel cage motors demand far less maintenance than the dc motors of WAP4. The second is that WAP5 and WAP7 have regenerative braking which, during retardation, recovers some of the train's enormous kinetic energy by converting it to electrical energy and sending it back into the overhead electrification line (OHE). The third is that these locos are far easier to drive. An additional plus point of WAP7, though not as important as the advantages listed above, is that it has somewhat higher performance ratings than WAP4, being capable of an additional 1350 HP (in the continuous mode) and 50 kN (in the transient mode). WAP5 has comparable power and significantly lower TE ratings than WAP4.

Ironically, it is this last and least significant factor which has till now has played possibly the largest role in determining the list of trains to get a three phase loco as regular link. As these locos are still a scant resource with less than 200 in service, only a limited number of trains can get them. In view of the energy saving aspect, the apparently logical decision would have been to use them on heavy trains which have frequent slowdowns and halts, so that the maximum energy could be recovered during operation. In some instances, such a rationale is indeed observed, as in the case of BDTS-ASR Paschim Express and ASR-BSP Chhattisgarh Express. In many other cases however, the performance advantage gets precedence over the power saving factor. Three phase locos are used on a large number of prestigious and fast trains with very limited halts, just for achieving faster section clearance. Some such examples are NDLS-HWH, NDLS-SDAH, NDLS-BCT, NZM-SBC and NZM-MAS Rajdhani Express, NDLS-BCT, DEE-YPR and NDLS-ALD Duronto Express, NDLS-LJN, NDLS-CNB and BCT-ADI Shatabdi Express and the recently introduced NDLS-BCT Premium Special Duronto Express. In September 2013, the link for NDLS-RJPB Rajdhani Express was permanently changed from MGS WAP4 to GZB WAP7 due to punctuality problems with the former link; the resulting improvement in run time was disproportionate to the modest advantage which WAP7 offers over its competitor.

The apparently large disparity between the performance of WAP4 and three phase locos in fact arises because WAP4 is very sensitive to the technique of the loco pilot (LP) driving it while the three phase locos are not. In these latter machines, the LP simply has to advance a joystick for acceleration, and

(*) Train has fluctuating link and WAP4 is one of the alternatives. Loco links obtained from [2] and from observations.

everything follows automatically. In WAP4 on the other hand, the LP must take the notches and shunts at just the right speeds so that the maximum acceleration may be obtained without the motor voltage and current straying beyond their tolerance values. This is a problem in optimization and is by no means trivial; in the absence of a standardized driving algorithm, the LP is reliant on his (*) skill and experience to devise a strategy of his own. Less skilful or inexperienced LPs often have undue fears about exceeding the limits, and hence drive very conservatively. Even many skilled LPs in fact do not have any set strategy and rely on instinct and intuition to take every additional notch/shunt as a spot decision – for this reason the same LP might accelerate quickly on one occasion but go slower an hour later. All these result in a large degree of variability in the output performance, as the following examples show. In repeated measurements of WAP4 hauled 23-24 coach Superfast trains in MGS-CNB sector, the time taken to accelerate from 30 km/hr to the maximum permissible speed (MPS) of 110 km/hr varied from as low as 3.5 minutes to as high as 8 minutes. The average, at more than 6 minutes, was closer to the higher figure. In measurements of 18-20 LHB coach Rajdhani loads on the same sector, the acceleration time from 40 km/hr to the MPS of 130 km/hr showed a minimum of under 4 minutes and a maximum of above 9 minutes. Once again, the average of 6.5 to 7 minutes was closer to the worse figure. In contrast, multiple measurements of the time taken by WAP7-hauled 18-20 coach Rajdhanis to accelerate from 30 km/hr to MPS show a much narrower dispersion with the minimum being around 2.8 minutes, the maximum 4.5 minutes and the average around 3.8 minutes. Data from WAP7 hauled Superfast runs also shows a similar trend although the total number of measurements we have taken is not adequate for a formal statistical treatment. Thus, going by the averages, WAP7 appears almost twice as powerful as WAP4, and even WAP5 appears far superior, though that is in contradiction to the specifications. It is this aspect of WAP4 performance which often makes it undesirable for a prestigious and fast train, where rapid acceleration from halts, caution orders and adverse signals is essential for a punctual run. To take another example, the loco link of 21-coach NDLS-BCT Rajdhani had to be changed in February-March 2014 from the existing GZB WAP5 due to wheel slip problems with the heavy load. Despite the relative scarcity of the loco, GZB WAP7 was immediately chosen as the new link and WAP4 of GZB or BRC shed was not even considered as a viable alternative.

The previous discussion motivates the need for a standardized driving algorithm which can eliminate these problems and enable all WAP4s to perform at their full potential. The proposal of such a strategy is the objective of the present Article. Numerous important trains across IR are still being allotted WAP4 as regular links, and the systematic adoption of a universal strategy will aid considerably in improving their punctuality performance. Moreover, it will also allow fresh allocation and/or reallocation of three phase locomotives on the basis of energy savings alone rather than section clearance considerations.

We end this Introduction with a brief outline of the structure of this Article. In Section 2 we deal with the torque speed characteristics of the diverted field series dc motor which is what is used in WAP4. In Section 3 we consider the motor along with the constraints and controls faced by the LP, and go on to propose general guidelines behind a strategy for optimized driving of any tap changer loco. In Section 4 we specialize to the case of WAP4 and explicitly describe the acceleration algorithms depending on the desired voltage and current levels. In Section 5 we consider the consequences of our proposed algorithms, using modelling and simulations to predict the acceleration time of various loads and the thermal burden of the acceleration run. We conclude with a summary and a brief discussion about the relationship between our strategies and the LPs' intrinsic intuition.

(*) In view of the overwhelming preponderance of males in the profession of LP, we use the masculine forms to denote both male and female LPs.

2. The Isolated series dc motor with diverted field

Inasmuch as the primary component of driving a tap changer locomotive is the control of its traction motors, we begin the main body of this Article with a detailed discussion of the torque-speed characteristics of these electric machines. The variety of motor used in WAP4 [3] is HS15250 which is a dc series motor [4-5]. In addition, a resistor is introduced in parallel to the field element to achieve flux weakening. The schematic circuit diagram of the dc series motor with diverted field is shown in Fig. 1. Note that at this stage the motor is 'isolated' i.e. we have not introduced any mechanism for controlling the motor. Also, we assume that the voltage and current flowing through the motor are always within the corresponding tolerance limits. While this assumption for a locomotive is fanciful, all these factors will be brought into the picture only after the basic characteristics have been discussed in detail.

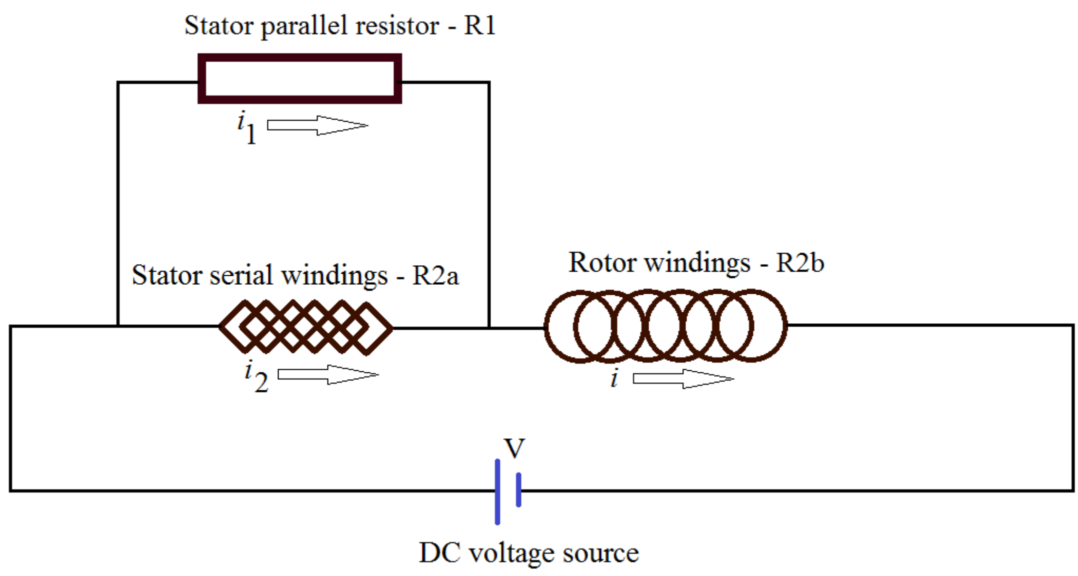

Figure 1 : *Schematic diagram of series dc motor with diverted field. The algebraic variable used to denote the resistance of each component has been indicated against it.*

Here, we define the resistance of the stator parallel resistor as R_1, that of the stator serial windings as R_{2a} and that of the rotor windings as R_{2b}. At first we assume that there is no resistor in parallel to the stator i.e. $R_1 \to \infty$. In such circumstances, a current i flows through both the stator and the rotor windings. A magnetic field is created by the stator windings at the rotor surface; in the absence of saturation (an assumption we will make throughout this work) its strength is proportional to the stator current hence we can write

$$B_s = k_2 i \quad , \tag{1}$$

where B_s is the stator field strength at the rotor surface and k_2 is a constant of proportionality which is an intrinsic property of the motor. The value of i can be found by a direct application of Ohm's law to the motor; before that however we need to take into consideration that when the motor runs, an emf is developed across the rotor. The source of this emf is the motional effect – viewing from the stator frame, when the rotor is spinning, its conductors are moving through the stator's magnetic field which is static. The relation $\mathbf{E} = \mathbf{v} \times \mathbf{B}$ tells us that the emf is proportional to the speed of the rotor and to the strength of the magnetic field [6]. The first term is equal to the rotor radius times its angular velocity ω about its axis. The second term might involve the magnetic fields created by both stator and rotor; however, since the rotor is not moving relative to its own field, only the stator field i.e. B_s will contribute. Hence we can write the magnitude of this emf as

$$|emf| = KB_s\omega \quad , \tag{2}$$

where K is another intrinsic constant of the motor.

Having got the magnitude of the emf, we must now determine its sign relative to V. A cumbersome consideration of the geometries of stator and rotor is short-circuited if we realize that from the rotor's viewpoint i.e. in the rotor frame, the emf appears to be generated by electromagnetic induction. For this process, there is Lenz's law to come to our aid – the induced emf always opposes the cause which produces it. Since the cause here is the relative motion between rotor and stator, the induced emf will try to reduce this motion i.e. *retard* the rotor. Hence, this emf is antagonistic to the applied V which *drives* the rotor, and must be opposite to V in sign. Because of this, this emf is referred to as the back-emf. The net voltage across the motor terminals is the superposition of the applied voltage and the back-emf (it is qualitatively obvious and a rigorous derivation may be found in [7]) and we can now write Ohm's law for the motor as

$$i = \frac{V - k_2 K\omega i}{R_{2a} + R_{2b}} \quad , \tag{3}$$

in which we have substituted (1) into (2). Letting $R_{tot} = R_{2a} + R_{2b}$, i.e. R_{tot} is the total resistance of the motor circuit, we can easily solve (3) to get

$$i = \frac{V}{R_{tot} + k_2 K\omega} \quad . \tag{4}$$

The torque of the motor arises because the rotor conductors are carrying a current in presence of a magnetic field. The relation $\mathbf{F} = i(\mathbf{l} \times \mathbf{B})$ for the force on a current wire in a magnetic field tells us that the torque (which is just force times radius) will be proportional to the rotor current and to the magnetic field. Since the rotor's own field cannot cause a torque upon it (an isolated current wire exerts no force on itself), once again the relevant field will be B_s. Putting these together, we get the expression for the torque Γ of the motor :

$$\Gamma = CiB_s = C_1 \left(\frac{V}{R_{tot} + k_2 K\omega} \right)^2 \quad , \tag{5}$$

where C and C_1 are again intrinsic constants of the motor. Equation (5) is the torque speed characteristic of the series dc motor. We note that this characteristic has been obtained by assuming the stator and rotor currents to be in their steady state (equilibrium) values. Hence (5) is also referred to as the steady state motor characteristic. The transient characteristics are obtained by considering the motor's dynamic model, an issue we will not go into here. Fig. 2 shows a typical plot of a motor's torque speed characteristic.

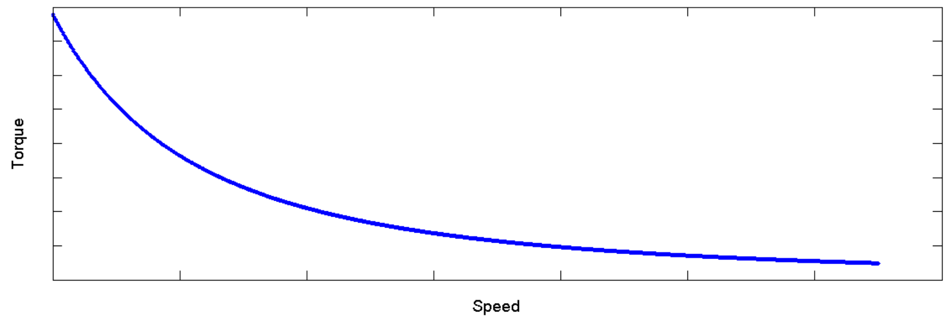

Figure 2 : *Torque speed characteristic of a dc series motor.*

Stephen Chapman [8] comments that the asymptotic dependence $\Gamma \propto 1/\omega^2$ is not usual; what perhaps matters more to us is that it is not useful. The power of the motor is the product of the torque and the angular velocity and the above implies that the power goes asymptotically as $1/\omega$ – the faster the motor spins, the weaker it gets. Obviously, such a characteristic is a disaster for a locomotive where a high power output is required all the way upto the train's MPS. It is to combat this problem that the process of field (or flux) weakening is introduced. This is done through the stator parallel resistor R_1, also known as the shunt resistor.

Let us first get a qualitative idea of field weakening. In the absence of R_1, the entire motor current flows through the stator windings. This creates a strong magnetic field, which starts generating a high back-emf the moment the motor speeds up. The decrease in motor performance as ω increases is primarily due to this back-emf, which limits the motor current. Hence if this emf can somehow be reduced, the performance can be augmented. This reduction is achieved by R_1 – in its presence, some of the motor current flows through it and thus gets diverted from the field windings. This causes the field to become weaker, in turn reducing the back-emf and increasing the total current through the motor. The increase in torque is partially offset by the decrease in magnetic field strength; however if the resistor values are chosen properly, a substantial improvement of motor performance can be achieved by this diversion of the field current.

Now we work out the quantitative aspects of field weakening. The parameters remain the same as in the previous calculation except that this time, R_1 is finite. The total current i splits up into two parts i_1 and i_2 which flow through R_1 and R_{2a} respectively. Basic circuit theory at once says

$$i_1 R_1 = i_2 R_{2a} \quad . \tag{6}$$

Since only the part i_2 and not the full i flows through the field windings, (1) will get modified to

$$B_s = k_2 i_2 \quad . \tag{7}$$

The physics behind the back-emf remains the same and we can write Ohm's law for the motor as

$$i = i_1 + i_2 = \frac{V - k_2 K \omega i_2}{R_{tot}} \quad , \tag{8}$$

where R_{tot} is the total resistance of the motor circuit. Equations (6) and (8) can be solved to obtain

$$i_2 = \frac{V}{R_{tot}(1+Rr) + k_2 K \omega} \quad , \tag{9a}$$

$$i = \frac{(1+Rr)V}{R_{tot}(1+Rr) + k_2 K \omega} \quad , \tag{9b}$$

where Rr (short for 'R-ratio') denotes the ratio R_{2a}/R_1. The equivalent of (5) readily follows as

$$\Gamma = C_1 i i_2 = \frac{C_1 (1+Rr) V^2}{\left[R_{tot}(1+Rr) + k_2 K \omega\right]^2} \quad . \tag{10}$$

This is the torque-speed characteristic of the series motor with diverted field. Figure 3 compares the curve of Fig. 2 with the characteristic for the same motor with field weakening resistor added. We see that after a certain speed, the resistor causes a boost in the torque output.

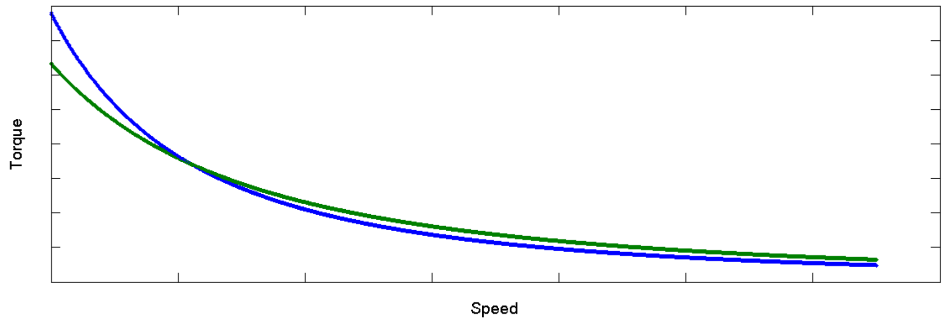

Figure 3 : *Torque speed characteristic of a dc motor with and without a shunt resistor. The blue line is taken from Fig. 2 and corresponds to no shunt resistor. The green line is with shunt resistor in place.*

3. The Motor in context : principles for good driving

The derivation of the torque speed characteristics of the isolated motor being completed, we now move on to the more realistic and more challenging case where the motor is connected to control apparatus and carries a set of tolerance values on its operating parameters. We will assume that the multiple motors of the locomotive are all connected in parallel, so that each motor is independent of the other. (In IR jargon, this is known as 6P configuration.) While we take the specific circuital and other details from WAP4, the nature of these controls and constraints is very general and is common to more or less any tap changer controlled '6P' locomotive. Hence the arguments of this Section, which are based only on this general structure, are applicable to all '6P' tap changer locos and not just WAP4. The schematic diagram of the traction circuit is presented in Fig. 4, where we

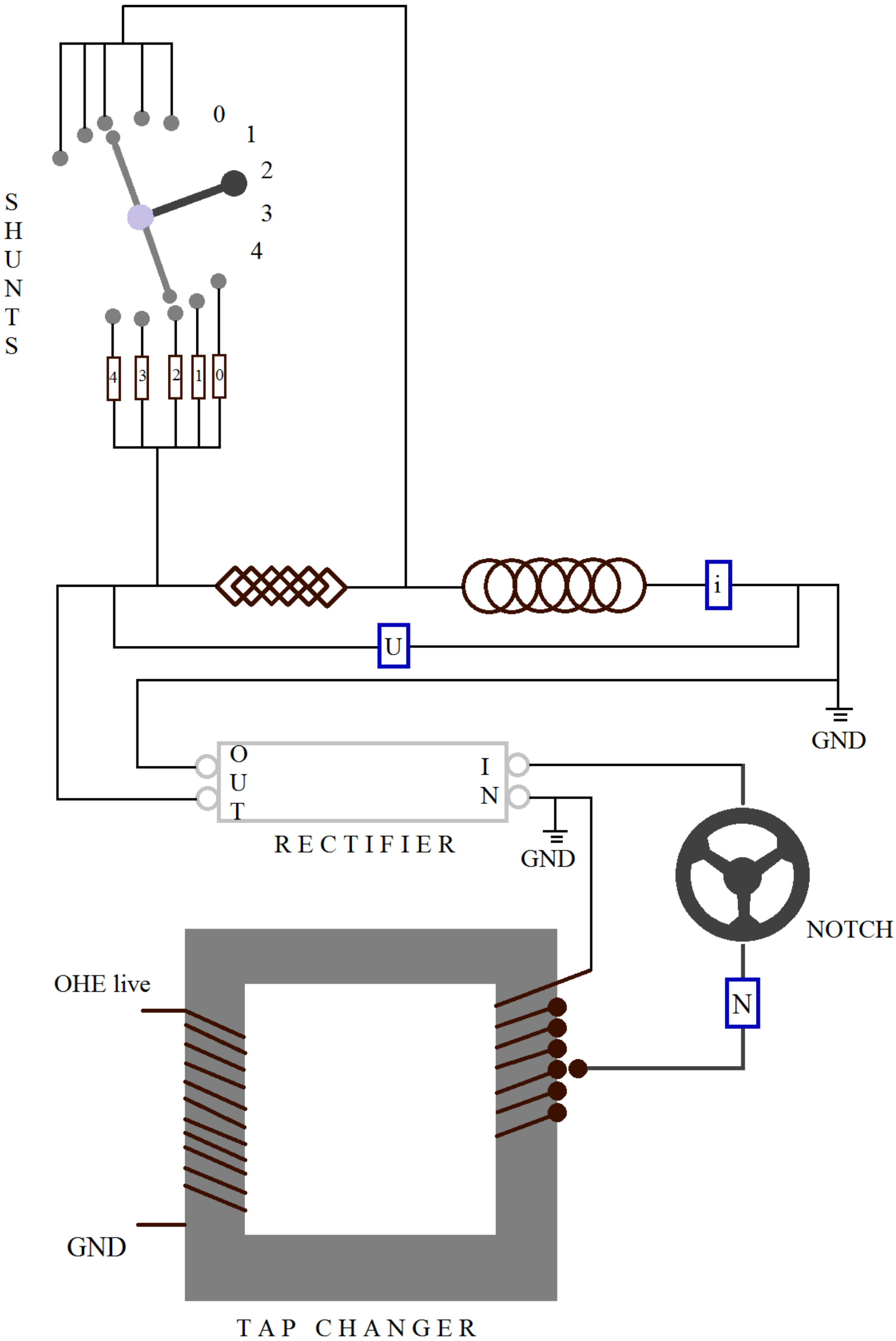

Figure 4 : *Schematic representation of traction circuit of WAP4.*

show only one of the six motors connected across the rectifier. It should be noted that the shunting lever in the loco pilot's cab applies the shunt simultaneously to all six motors and not to just one of them.

There are two ways in which the traction motors of a tap changer locomotive are controlled. The first is by varying the voltage V applied across the motor terminals. This variation is of course achieved by the tap changer [9], whose primary is connected to the overhead electrification line (OHE) and whose secondary forms the variable output. This output is fed to a rectifier which converts it to dc for the motors. In the LP's cab, the tap changer output is controlled by the notching lever or wheel. First notch corresponds to one turn of the secondary coil in use, second notch to two turns and so on. Clearly, for constant tap changer input, the output is proportional to the notch number N, and if the rectifier and other circuitry are linear (which they generally are), so is the voltage applied across the motor. The maximum number of notches varies from loco to loco; in WAP4 it is 32. The second way of motor control is through variation of the field weakening or shunt resistor R_1 (and hence of the ratio Rr). This is achieved by having multiple resistors in parallel with the field windings but with their circuits all open – the LP must use the shunting lever to close the circuit of any one parallel resistor he desires to employ. Each resistor corresponds to a different position of the shunting lever. In WAP4 the shunt has five positions labelled 0, 1, 2, 3 and 4 – the zero position corresponds to R_1 virtually infinite while higher positions progressively decrease its value, thereby increasing the ratio Rr. In what follows, the numerical position of the shunt lever will be denoted by the variable S.

For every control there must be feedback. In WAP4 this is provided by the voltmeter which measures V (two voltmeters are provided to measure the voltage across two of the motors but in normal operation the values displayed by them are equal) and the ammeter which measures i. There is no tachometer, but since in ordinary conditions (no wheel slip) the train speed v is proportional to the motor rpm, the speedometer suffices for this purpose. The notch setting N is generally displayed on an electronic indicator. In addition there is an auxiliary voltmeter to measure the OHE voltage and the voltage supply to components other than the traction motors.

We now mention the tolerance limits of the various operating parameters for the WAP4's motor. The voltage limit is 750 V (in a few derated specimens it is 725 V or 700 V). The continuous current rating is 900 A and the ten-minutes current rating is 1100 A. In newer and/or better-maintained locos, a short term current of 1300 A is also allowed for a maximum duration of two minutes. The tolerance limits are generally enforced by a relay or equivalent circuitry which causes the notches to automatically regress if the limits are exceeded. However, since there is always the possibility of malfunction of this circuitry, LPs are generally recommended to consciously stay within the tolerance limits instead of relying fully on the electronics.

At this point we are finally in a position to formally state the primary problem which we have addressed in this Article. *During acceleration of the train, in what manner must the loco pilot select the notch and shunt settings so as to obtain the maximum possible torque output from the traction motors without exceeding the tolerance limits on their operating parameters ?* The remainder of this Section answers this question in general terms and the next Section translates the general answer into language specific to WAP4.

The first task at hand is to determine the functional forms of the notch number N and the shunt setting S which the LP must use during acceleration. In the most general representation, the present problem can be cast at once as a study in classical control – the output variables N and S are functions of the input variables v, V and i. However, in a situation such as the present one, our primary objective has to be to keep things as simple as possible – after all, the LPs are not conducting a laboratory procedure but running a real train. A complex driving algorithm will merely draw negative responses so far as implementation is concerned. Accordingly we now reduce *N* and *S* to the simplest possible functional form. As we mentioned above, if the OHE voltage is known and constant, *V* gets determined by *N* alone. From (10), *i* is influenced by *V* (hence *N*), *Rr* (which depends on *S*) and ω (which is proportional to *v*). Thus, if *N*, *S* and *v* are specified, *V* and *i* are fixed automatically. Hence an enumeration of triplets (*N*,*S*,*v*) for various values of *v* will be sufficient for a complete solution to the problem. This of course assumes that OHE voltage is constant during acceleration; since acceleration runs especially on passenger trains do not take much time, this assumption is fairly reasonable. For greater precision, we can construct sets of (*N*,*S*,*v*) triplets corresponding to various values of OHE voltage and the LP can be instructed to switch from one set to another if the voltage changes during acceleration.

When the speed is low, the natural choice of shunt setting is the zero value. Indeed, at low speed there is little back-emf anyway so the shunts, which are designed just to reduce this emf, are not required. Practically, taking a few notches at low speed immediately results in *i* reaching its tolerance value. Right now the LP can do nothing further. Maximum *i* on zero shunt however corresponds to maximum torque, which in turn means maximum TE and acceleration. As the train speed increases, *i* will come down rapidly as per (9b), and the question arises as to whether the LP should take a notch or a shunt to counteract this decrease. Indeed, at any given *v*, there might be several pairs (*N*,*S*) which all correspond to the same value of current – which pair is best ? This issue is resolved by writing (10) in the form

$$\Gamma = \frac{C_1 i^2}{1 + Rr} \quad . \tag{11}$$

Since higher shunt settings mean higher values of *Rr*, for a constant *i*, the torque is greater for the lower position of the shunt. Hence, whenever possible, the LP should try to attain the tolerance current value at the lowest possible shunt.

Thus, after first hitting tolerance current at low speed, low notch and zero shunt, the LP should wait for the train to accelerate and the current to decrease to such a level that the next notch may be taken without going over the limit. At this point, he should increment the notch level by one, and then again wait before yet another notch can be taken. In this manner, the LP should continue taking notches one after another until either the maximum notch level or the tolerance limit on *V* has been reached. For maximum motor utilization, *i* should jump up all the way to its tolerance value after each notch increment. To determine the optimal manner of notching with increase in speed, we examine (9b) to see what kind of function $V(\omega)$ will serve to keep *i* constant. The answer is evident on inspection – the desired *V* must be a linear function of ω. Hence at each notch increment, where *i* should be constant and equal to its limit, the incremented *N* should be proportional to *v*. In other words, the successive notches should be incremented at a uniform rate in speed, say one additional notch after every 5 km/hr speed gain.

When the limiting notch has been reached on zero shunt, it is no longer possible to compensate the decrease in current by taking any further notches. It is now that the shunts come into play. After reaching the last notch, the LP must wait for the current to decrease to a level such that the first shunt may be taken without crossing the limit. If at this point, the torque on first shunt exceeds that on zero shunt, then he should take the first shunt. Whether this torque relation will hold true or not depends on the values of the resistances and hence on the particular loco in question. If it does not hold at this point, then it will start to hold at a higher speed (Fig. 3 is noteworthy here) and the transition should be made at that speed. In a like manner, the second shunt should follow the first shunt, the third follow the second and so on. In some locomotives it is observed that *V* decreases after taking of shunts. This is not the expected behaviour as per the ideal characteristics, and it happens because of the non-idealities in the rectifier as a voltage source. An ideal voltage source should have an impedance of zero; the practical source has small resistance but not zero. With each shunt, the motor resistance R_{tot} decreases hence a greater fraction of the voltage drop occurs across the rectifier itself instead of the motor. This decrease in *V* worsens the motor performance for no reason, hence it should be immediately compensated by taking extra notches as required. During the entire shunting phase, *V* should be kept as close to its tolerance value as is possible.

Although acceleration is the primary component which affects the overall timings of a WAP4-driven passenger run, another factor which also plays a role is the tightness with which MPS (*) is maintained by the LP. While good LPs manage to keep the speed within 2 km/hr of MPS over extended periods of time, less skilful LPs often drift from MPS by larger amounts. Since overspeeding is dangerous and hence forbidden, these LPs always underspeed, often by 5 km/hr or even more. In three-phase locos on the other hand, speed maintenance is achieved electronically by the press of a button hence this problem does not normally arise. Accordingly we now outline some strategies to hold the speed constant on a tap changer loco.

The key to achieving constancy of speed is to find the balancing point i.e. the notch and shunt setting at which the TE of the loco will just equal the train resistance at MPS. For most passenger trains, the balancing power is significantly less than the full power of the loco. The balancing notch and shunt settings are typically determined by hit and trial – if the train tends to overspeed, then reduce the notch or shunt and if it tends to underspeed then increase the notch or shunt. It might very well happen that the precise balancing voltage corresponds to a fractional notch, in which case a time-partition between two adjacent notches will be required to balance the train. A bang-bang strategy will have to be adopted with the lower notch selected when the speed rises and the higher one used when it falls. Since the power on both the higher and lower notch settings is very close to the ideal, the oscillations in speed should be very slow and the banging limits should not be more than 1 km/hr apart. Even after the balancing point is found once, that does not mean that the train speed will remain constant for all time. Terrain features like gradients and curves, and OHE voltage fluctuations cause the train speed to deviate from the set value. The time scale of these deviations is generally quite large however and the LP should be able to react as soon as a 1-2 km/hr error is encountered. The strength of the reaction should be dependent on the rate at which the train speed is changing – a slow change can be offset by increasing or decreasing a single notch while a rapid change should be attacked with more notches and/or shunts as required. It should be noted that fluctuations due to change in OHE voltage alone can be eliminated by adjusting the notch level so that the voltmeter reading *V* remains constant at all times.

With this we complete the general description of the optimized driving algorithm for any tap changer loco. In a way, our prescriptions constitute a clarification and elaboration of the very general comments made in [10]. In the next Section we take the specific case of WAP4, obtain numerical values of its various parameters and hence derive the specific triplets (*N*,*S*,*v*) which will enable the LP to get maximum performance out of it.

(*) In this Article the abbreviation MPS refers to maximum permissible speed only. We do *not* follow the convention found in some documents e.g. [10] of using 'MPS' to denote the shunting lever.

4. WAP4 : Algorithms and strategies

Now that the general principles for good driving of a tap changer loco have been established, we can proceed to the specific case of WAP4 locomotive. For a strategy which can be implemented by a LP on the run, we must talk not in terms of abstract concepts but in terms of hard, concrete numbers. These numbers can be specified only if we know the numerical values of the various motor constants. Some of these constants can be obtained from specification sheets and brochures; some however are not mentioned in the literature. Even for the specified parameters, there can be considerable gap between theory and practice since values change during actual usage. Accordingly, we have first evaluated all the motor parameters by interpolation from dozens of data sets obtained from actual runs of WAP4s with passenger trains. Then we have decided on the final values by corroborating these figures with the specifications in manuals. The references used here are [11-13].

Let us enumerate the list of motor parameters which will have to be determined for a complete numerical specification of the strategies. From the characteristics (9) and (10), the relevant parameters are k_2K, Rr and R_{tot}. Since Rr is different for each shunt, we have to determine its values corresponding to all the shunts. We will label these values with the subscript S i.e. Rr on 2nd shunt will be denoted as Rr_2. R_{tot} also changes with the shunt value hence we need to find this parameter too for each shunt. This procedure can be obviated however if we can separately determine R_{2b} and R_{2a} on zero shunt. Then, using the relation

$$R_{tot} = R_{2b} + \frac{R_{2a}}{1+Rr} \quad , \tag{12}$$

and the determined values of Rr at each shunt, we will be able to get R_{tot} for each shunt. The parameter C_1 of (10) is an overall normalization constant for the torque and will not affect the strategies in any way.

Before presenting the values which we have obtained, we would like to make a brief discussion on the units we will use. Normally, internally closed systems of units such as SI or cgs are recommended for calculations as any new parameter automatically comes out in the same system of units. However, for this work we have made an exception which we feel is more convenient in the long run. We will measure V in kV, i in kA and ω in km/hr. We can hear the howls of protest from the readers at this apparently glaring dimensional inconsistency so we hasten to clarify. When we take ω in km/hr we do not mean that the motor rotation rate is actually *measured* in those units; rather, exploiting the proportionality between v and ω, we have *defined* new units of ω in such a manner that one unit of ω of the motor corresponds to 1 km/hr of the train. Hence, the *numerical value* of ω in our units will be equal to the *numerical value* of v in km/hr. The reason for this unusual choice of units is that while doing the actual computations we will not have to bother about cumbersome numerical conversion factors. For more conventional units of ω, we use the fact that the wheel diameter is 1092 mm in new condition and 1016 mm in full worn; assuming an in-between value we can get the following rough and ready conversion between motor rotation rate in rpm and train speed in km/hr :

$$\text{(motor rpm)} = 5 \times \text{(gear ratio)} \times \text{(train km/hr)} \quad . \tag{13}$$

For WAP4, the gear ratio is 58/23 which is about 2.5 hence the motor rotation rate in rpm is about 12.5 times the train speed in km/hr.

The first fact which emerges from the references is that at zero shunt, 5 percent of the current is diverted from the field. This corresponds to Rr_0=0.05, which we have used. Fixing this, we have interpolated the actual data to obtain the best fit values k_2K=0.0062 and R_{tot0}=0.26. The ratio in which this gets split between R_{2a} and R_{2b} is again found from brochures [11] and [12] : the best values are R_{2a}=0.09 and R_{2b}=0.17. Since the resistances can vary by as much as 10 percent [11], there is no point in specifying the values to greater precision. We now need to find the values of the shunts, and the starting point for this is the empirical rule taught in driving schools that the current increases by 100 A immediately after each of the first three shunt transitions and by 150 A after the fourth transition. This information is incomplete as it does not specify the speed and voltage condition at which this phenomenon should happen. The real time data sets supply the missing pieces of the puzzle : the specified current increase occurs when V=0.75 and i=1.05 just before the transition. More careful analysis of the data reveals that the observed current increments at the first two shunts are somewhat lower than 100 A and are of the order of 75 A only. The observed current increases at the third and fourth transitions are indeed very close to 100 A and 150 A respectively. Using this information we obtain the following values of Rr for the four shunts : Rr_1=0.15, Rr_2=0.26, Rr_3=0.42, Rr_4=0.70.

With all the motor parameters in our bag, we can now express the general strategies of the previous Section in quantitative terms. In Tables 1 and 2 we indicate the speeds at which the various notch and shunt transitions should be taken to maintain maximum motor current at i=1.1 kA and i=1.25 kA respectively. These of course correspond to the two most common current limits tolerated by WAP4s; since 1.3 kA is a maximum limit we have taken 50 A less as a safety factor. Since the maximum permissible notch level as well as the notching pattern varies with changing OHE voltage, we indicate the strategies for three different voltage levels, corresponding to V=0.75 being attained at N=24, N=27 and N=30 respectively. The shunting transitions have been calculated assuming that the voltage remains 0.75 throughout – compensating notches need to be taken by the LP if necessary and have not been shown.

Traction motor current : 1.1 kA					
0 Shunt					
OHE HI		OHE MED		OHE LO	
Speed	Notch	Speed	Notch	Speed	Notch
10	11	10	12	10	13
15	12	13	13	11	14
20	13	17	14	15	15
25	14	21	15	19	16
29	15	26	16	23	17
34	16	30	17	26	18
39	17	34	18	30	19
44	18	38	19	34	20
49	19	43	20	38	21
53	20	47	21	42	22
58	21	51	22	46	23
63	22	56	23	50	24
68	23	60	24	53	25
73	24	64	25	57	26
		68	26	61	27
		73	27	65	28
				69	29
				73	30
1st Shunt			81		
2nd Shunt			90		
3rd Shunt			103		
4th Shunt			126		

Table 1 : *Speeds for the various notch and shunt transitions for 1.1 kA in the traction motors. Please see Table 2 overleaf before continuing with the bulk text.*

These Tables however have certain prominent limitations. The first is that only three levels of OHE voltage have been considered but in reality the OHE can be at any level between these three. What is the LP supposed to do in that case ? Second is the fact that the motor parameters can vary significantly. As we have already mentioned, the resistance allows for 10 percent variation on either side of the mean. The parameter k_2K is also going to show apparent variation from loco to loco on account of differences in wheel size. For a loco with almost new wheels, 100 km/hr might be equivalent to 1230 rpm, while for a loco with heavily worn wheels it might correspond to 1310 rpm. Since the actual motor variables depend upon its rpm and not the train speed, k_2K will have to be varied to accurately cover for these two cases. Then are we going to construct a separate table for each of hundreds of combinations of R_{tot} and k_2K ?

One way of resolving the above dilemmas would be to propose algorithms based on ammeter readings which are absolute. But as mentioned in the previous Section, that would not be practical to implement. The resolution is achieved by noting that though the absolute speeds of the various transitions can vary widely with change in parameters, the *difference in speed between successive transitions* changes only by a small value. Thus, the first column of Table 1 features notch increments at 5 km/hr intervals; for a different set of parameters this interval might change to 5.2 or 5.3 km/hr, which is quite a small change. The shunting intervals too are quite robust to small variation in

Traction motor current : 1.25 kA					
0 Shunt					
OHE HI		OHE MED		OHE LO	
Speed	Notch	Speed	Notch	Speed	Notch
10	12	10	14	10	15
12	13	14	15	11	16
16	14	17	16	15	17
21	15	21	17	18	18
25	16	25	18	22	19
29	17	29	19	25	20
33	18	32	20	28	21
38	19	36	21	32	22
42	20	40	22	35	23
46	21	44	23	38	24
50	22	48	24	42	25
55	23	51	25	45	26
59	24	55	26	49	27
		59	27	52	28
				55	29
				59	30
1st Shunt			66		
2nd Shunt			73		
3rd Shunt			84		
4th Shunt			104		

Table 2 : *Speeds for various notch and shunt transitions for 1.25 kA in the traction motors.*

parameters. And the trend in the notching intervals as OHE voltage varies is also readily apparent – as the line voltage decreases, the interval becomes lower and lower. Periodically the LP will have to check the ammeter to verify that things are all right but on the whole he can just proceed with notching and shunting at the prescribed intervals. For additional convenience on run, we may round off the shunting intervals to the appropriate multiple of 5 km/hr – that is easier for LPs to remember and execute and causes minimal decrease of loco performance. Finally, we mention two things related to the endpoints of the acceleration run. Before the run starts, the couplers of the train are slack while during acceleration they are in tension. If at the start of the run the TE is applied too rapidly, the couplers change from slack to taut with a big jerk. Hence we recommend the LP to take a few notches at first, verify that the train has started accelerating and only then crank up to hundred percent TE. At the other end of the run, according to the Tables some of the shunt transitions are very close to the MPS of typical trains. For instance, in Table 1, the third and fourth shunt transition speeds are very close to the MPS of Mail/Express and Rajdhani/Duronto type trains respectively. We feel that in general, a transition very close to MPS is best avoided : since the power will have to be taken down anyway at MPS, the transition will just result in a short burst of high current causing increased wear and tear of the motor and a minuscule gain in time. Of course, an exception must be made if the acceleration before the transition has degraded to such a level that attaining MPS will require an inordinate time.

With all these modifications in place, the final sheet describing our algorithm is given on the next page. The format of this page is such that it can directly be printed and given to an LP or loco inspector for use on run.

Algorithm for acceleration of WAP4 locomotive

Note : Speeds written in the following format assumed to be in km/hr : **123**

For 1100 A in traction motor :

1. At start of acceleration run, keep shunt set to 0. Use a small current to bring the couplers to tension and then take notches quickly until ammeter reading becomes 1100 A.
2. From this point on keep taking one additional notch at equal intervals of speed. This interval is **5** if OHE voltage is high, **4** if OHE voltage is low. Just before taking each notch, your ammeter should read about 1050 A.
3. Stop taking notches when voltmeter reads 750 V. This should happen at speed around **75**. Note the exact speed at which you have taken the last notch.
4. Starting from the speed noted above, take the four shunts at speed intervals of **10**, **10**, **10** and **25** respectively. Just before taking 1^{st}, 2^{nd} and 3^{rd} shunt your ammeter should read 1000 A or lower. Just before taking 4^{th} shunt your ammeter should read 950 A or lower. However, a shunt transition is best avoided if you are close to the train MPS and the acceleration is still appreciable.
5. Take additional notches after successive shunts to compensate voltage drop due to shunting.

For 1250 A in traction motor :

1. At start of acceleration run, keep shunt set to 0. Use a small current to bring the couplers to tension and then take notches quickly until ammeter reading becomes 1250 A.
2. From this point on keep taking one additional notch at equal intervals of speed. This interval is **4.5** if OHE voltage is high, **3.5** if OHE voltage is low. Just before taking each notch, your ammeter should read 1200 A or lower.
3. Stop taking notches when voltmeter reads 750 V. This should happen at speed around **60**. Note the exact speed at which you have taken the last notch.
4. Starting from the speed noted above, take the four shunts at speed intervals of **10**, **10**, **10** and **15** respectively. Just before taking 1^{st}, 2^{nd} and 3^{rd} shunt your ammeter should read 1150 A or lower. Just before taking 4^{th} shunt your ammeter should read 1100 A or lower. However, a shunt transition is best avoided if you are close to the train MPS and the acceleration is still appreciable.
5. Take additional notches after successive shunts to compensate voltage drop due to shunting.

It should be noted that the strategies presented above are in very good agreement with the techniques already being used by good LPs when achieving a quick acceleration run. This finally completes the acceleration algorithm which we had set out to propose in this Article. In the next Section we will use textbook as well as impromptu formulae for train resistance to estimate the time which WAP4 driven as per these algorithms will take to accelerate certain standard load combinations to typical maximum permissible speeds. In that Section we will also suggest some notch and shunt combinations at which these loads can be balanced at their MPS.

5. Consequences of our algorithms

'Consequences' can mean a variety of things. In this case we are referring to two primary aspects – (a) the time taken for the loco to accelerate a given load to a given speed and (b) the increase in temperature of the traction motor at the end of the acceleration run. This latter parameter is important because the prolonged high currents in acceleration may potentially cause the motor to overheat, with disastrous results. Indeed, the entire concept of different current ratings for different durations is based on thermal considerations – exceeding either the current or the duration can lead to overheating and motor failure.

A. Kinematics

The two primary types of passenger rakes in existence today are self-generating (SG) ICF coaches for Mail/Express and Superfast trains and end-on-generating (EOG) LHB coaches for Rajdhani, Shatabdi and Duronto Expresses. Increasingly however, LHB coaches are being used on Superfasts too. To actually compute the acceleration times of these trains we will need numbers for both the loco TE and the train drag. The first is found from the constant C_1 which has hitherto been left variable. Since the TE is directly proportional to the motor torque, we can choose C_1 in (10) such that Γ becomes equal to the TE. Using the known result that the maximum TE of WAP4, which occurs at 1.3 kA in the traction motors, is 30.8 tonnes of force, we get the numerical value C_1=19. The train drag formulae are given on the website by Mahesh Jain [14]. The drag equals the mass m of the train times a factor which has the form $a+bv+cv^2$. For LHB coaches on level track, the values of a, b and c according to [15] are 0.699, 0.0215 and 0.0000835 respectively if the train mass is in tonnes, speed in km/hr and drag in kgf. For ICF coaches, the corresponding numbers are 1.43, 0.0054 and 0.000253 respectively. Thus the drag formulae may be written as

$$drag_{\mathrm{LHB}} = m\left(0.699 + 0.0215v + 0.0000835v^2\right) \quad , \tag{14a}$$

$$drag_{\mathrm{ICF}} = m\left(1.43 + 0.0054v + 0.000253v^2\right) \quad . \tag{14b}$$

A formula is also given for the drag force on the loco itself. We mention that the convenient unit of acceleration of a train is km/hr.s while calculations in tonnes and kgf give the acceleration in terms of g which is the acceleration due to gravity. The relation $1g$=35.28 km/hr.s connects the two systems.

An additional factor which might affect the train acceleration is the fact that (in ideal condition) its wheels roll without slipping on the track. Whenever there is rolling without slipping, acceleration is reduced. For example, a ball rolling down an incline attains only 5/7 of the speed of a box sliding frictionlessly down the same incline. Likewise, the loco may exert a force F on the coaches but due to the rotation of their wheels, the acceleration will be less than F/m. The correction can be evaluated by drawing a force diagram but an easier method is probably to use energy conservation. Since friction at the wheels does no work, the total work done by the TE must be equal to the gain in translational kinetic energy of the train plus the gain in rotational kinetic energy of the axles. Letting n be the number of axles and I the moment of inertia of each axle, we readily have the relation

$$F\mathrm{d}x = \frac{1}{2}m\mathrm{d}(v^2) + \frac{1}{2}nI\mathrm{d}(\Omega^2) \quad , \tag{15}$$

where dx is the infinitesimal displacement of the train and Ω is the angular velocity of the axles. This in turn is written as

$$Fv\mathrm{d}t = mv\mathrm{d}v + nI\Omega\mathrm{d}\Omega \quad . \tag{16}$$

Using the rolling without slipping condition, $v=\Omega r$ where r is the wheel radius, we cancel the common factor of v from both sides to get

$$\frac{\mathrm{d}v}{\mathrm{d}t} = \frac{F}{m + nI/r^2} \quad . \tag{17}$$

Thus, the effect of rolling without slipping is to make the train appear heavier by an amount nI/r^2. Estimating I from the dimensions data given in the LHB maintenance manual [15] and using the value of r specified there, we obtain this correction to be around 1.5 tonnes per LHB coach. It should be noted that this effective mass should not be used in the calculation of train drag, but only in the calculation of train acceleration after the net force has been evaluated as the loco TE minus the drag (for ordinary train mass).

In Table 3 we present the acceleration time for different LHB EOG loads on level track from 30 km/hr to 110, 120, 130 and 140 km/hr (more precisely 109, 119, 129 and 139 km/hr since the LP will have to power down at this point), computed on the basis of Tables 1 and 2 and drag formula (14a). For definiteness we assume that the OHE voltage is such that V=0.75 is attained at 27th notch. We include the data for 140 km/hr as it takes into account the possibility of speed upgradation of tracks in the near future. WAP4 is already certified for 140 km/hr. In February 2014, speed trials of 160 km/hr were conducted in CNB-MGS sector; perhaps significantly, the loco used for the trials was a WAP4. We consider three different types of loads namely 15, 18 and 21 LHB coaches. For 15 coach load, the coach consist has been assumed as that of NDLS-BBS Rajdhani Express i.e. 1H, 2A, 9B, 1PC and 2GC where H, A, B, PC and GC refer to AC First, AC Two-Tier Sleeper, AC Three-Tier Sleeper, Pantry Car/Hot Buffet Car and Generator Car respectively. Using the gross weights (in line with convention we use the word 'weight' to mean 'mass') of each type of coach from the manual, the train weight is 740 tonnes excluding the loco. For 18 coach load, the assumed consist is of NZM-MAS Rajdhani Express i.e. 1H, 5A, 9B, 1PC and 2GC, amounting to a total weight of 880 tonnes excluding loco. Finally, for 21 coach load, the assumed consist is taken from NDLS-RJPB Rajdhani Express i.e. 2H, 7A, 8B, 2PC and 2GC for a gross weight of 1020 tonnes excluding loco. For the total train mass, the extra effective mass and the loco mass (which is taken as 113 tonnes) are added. The entire mass is then rounded off to the nearest multiple of 10 tonnes. Along with the acceleration time, we also quote the distance used up in the acceleration run (the "take-off length"). As per our recommendations, the fourth shunt transition which must be made at 126 km/hr has been excluded for the 30-130 km/hr data sets but included in the 30-140 km/hr calculations. Finally, consistent with the errors inherent in modelling, each acceleration time has been rounded off to the nearest multiple of 5 seconds.

Speed range (km/hr)	Current (kA)	15 Load (740 ton)		18 Load (880 ton)		21 Load (1020 ton)	
		Time (mmss)	Distance (km)	Time (mmss)	Distance (km)	Time (mmss)	Distance (km)
30-109	1.1	0155	2.4	0220	2.8	0245	3.3
	1.25	0140	2.1	0200	2.5	0220	2.9
30-119	1.1	0220	3.1	0250	3.7	0320	4.4
	1.25	0200	2.7	0225	3.3	0250	3.9
30-129	1.1	0250	4.1	0325	5.0	0400	5.9
	1.25	0225	3.6	0255	4.3	0330	5.2
30-139	1.1	0320	5.1	0400	6.3	0445	7.7
	1.25	0255	4.7	0335	5.7	0415	6.9

Table 3 : *Time and distance required by various LHB loads to accelerate from a caution order of 30 km/hr to a range of maximum permissible speeds. The drag on the coaches is as per (14a). The time is displayed as minutes and seconds e. g. 0123 means 1 min, 23 s.*

Because of higher speed potential and increasing applicability of LHB coaches (*), they form the primary focus of this section. Nevertheless we would like to mention that according to the proposed strategies and formula (14b), for 24 ICF coach train of mass 1350 tonnes excluding loco, acceleration from 30 km/hr to 109 km/hr takes 4 min 0 s and 5.0 km with 1.1 kA and 3 min 25 s and 4.3 km with 1.25 kA strategy.

Surprisingly, while the simulation results obtained for ICF coaches show excellent agreement with real runs, the figures in Table 3 for LHB coaches exhibit significant disparity with experiment. In practice, a time in excess of three minutes was required for acceleration of a 15 coach LHB load from 30 km/hr to 129 km/hr with a combination of 1.1 kA and 1.25 kA strategies being followed. A time of about 3 min 45 s was observed for the same speed range for a 19 coach train with 1.25 kA strategy being followed. Checks show that the balancing power at MPS predicted on the basis of drag formula (14a) is significantly lower than the actual balancing power determined on run. For a 15 coach load, (14a) gives a drag force of 3.8 tonnes at 130 km/hr while in experimental runs, NDLS-BBS Rajdhani had to be balanced at MPS at a motor voltage of 650-700 V and a shunt setting of zero, which corresponds to a TE exceeding 7 tonnes. Likewise, for a 19 coach 930 tonne load, (14a) predicts a drag of 4.8 tonnes at 130 km/hr while in reality, NDLS-DBRT Rajdhani had to be balanced at MPS at almost 700 V across the motor and 2nd shunt, which corresponds to more than 8.5 tonnes of TE. Accordingly, formula (14a) needs to be modified to make it closer to reality. Examination of the predicted and experimental speed-time curves shows that almost all the deviation occurs at the higher speed range. Accordingly we keep intact the first two terms on the right hand side of (14a) and alter only the quadratic term. The value *c*=0.000345 (note : only three ciphers after the decimal point!) is found to produce a good match with the balancing power observed in practice hence we now re-compute Table 3 with the modified expression for the train drag, which we summarize below :

$$drag_{\text{LHB}} = m\left(0.699 + 0.0215v + 0.000345v^2\right) \quad . \tag{18}$$

(*) In April 2014, three Superfasts with LHB rake were upgraded for operation at 130 km/hr, thus creating further opportunities for WAP4 utilization at high speed.

Before presenting the modified results we would like to mention an observation we have made over the last three years. We have seen that with WAP7 hauled LHB Rajdhani Express, there has been a steady drop in acceleration performance over this time. While timings of 3 minutes or lower for 30-130 km/hr were commonplace in 2011-12, they have increased to 3.5 minutes or more over the last few months. All the increase has been observed at the higher speed range, hence it is possible that the increased drag is somehow related to the increasing age and/or maintenance practices of the coaches.

We are now ready to present the modified acceleration time and distance figures for the LHB coaches with increased drag, and we do so in Table 4, where once again the timings are rounded off to the nearest multiple of 5 seconds.

Speed range (km/hr)	Current (kA)	15 Load (740 ton)		18 Load (880 ton)		21 Load (1020 ton)	
		Time (mmss)	Distance (km)	Time (mmss)	Distance (km)	Time (mmss)	Distance (km)
30-109	1.1	0205	2.6	0235	3.3	0305	4.0
	1.25	0150	2.3	0215	2.8	0235	3.4
30-119	1.1	0235	3.6	0315	4.7	0400	5.7
	1.25	0215	3.1	0245	3.9	0320	4.8
30-129	1.1	0320	5.0	0420	6.8	0535	9.0
	1.25	0250	4.3	0335	5.6	0435	7.3
30-139	1.1	0410	6.9	0535	9.7	0810	14.9
	1.25	0340	6.2	0500	8.7	0720	13.3

Table 4 : *Same as Table 3 except that formula (18) for train drag is employed, which gives rise to significantly higher times and distances.*

With this we complete our discussion on the acceleration characteristics of trains with WAP4 locos driven as per our proposed strategies. It is also interesting to note that the results of our simulations indicate significantly lower acceleration times and distances than the computations done in [16]. As per our promises at the end of the previous Section, we now present the typical notch and shunt combinations for balancing these loads at various speeds. For definiteness we once again assume that V=0.75 kV is attained at the 27th notch. The results, using both drag formulae (14a) and (18), are presented in Table 5.

MPS	15 Load (740 ton)		18 Load (880 ton)		21 Load (1020 ton)	
	drag lo (N,S)	drag hi (N,S)	drag lo (N,S)	drag hi (N,S)	drag lo (N,S)	drag hi (N,S)
110	(13-14,0)	(18,0)	(14-15,0)	(19-20,0)	(16,0)	(21-22,0)
120	(15-16,0)	(20-21,0)	(16-17,0)	(22-23,0)	(17-18,0)	(24,0)
130	(17,0)	(23-24,0)	(18-19,0)	(24-25,1)	(19-20,0)	(25-26,2)
140	(18-19,0)	(24-25,2)	(20-21,0)	(24-25,3)	(21-22,0)	(26,4)

Table 5 : *Typical notch and shunt settings at which standard LHB loads will be balanced at various maximum permissible speeds. It is assumed that 27th notch corresponds to 750 V across the traction motor. When two adjacent notches are listed it means that a combination of the two is required for balancing. Cases have been covered assuming both low drag (14a) and high drag (18).*

It should be noted that as per the higher drag formula, almost the maximum power is being required for balancing a 21 coach load at MPS. On NDLS-BCT Rajdhani Express however it is observed that less power is required to maintain 140 km/hr in the stretch where that speed is permitted. The actual drag of the train will vary from rake to rake, and will be somewhere in between the two bounds (14a) and (18). Before concluding this discussion we present a plot of the mechanical power developed by the loco as a function of speed. We consider two cases – the continuous rating and the peak rating. The commonly accepted figures for these two cases are 5080 and 5350 HP respectively [12], [3]. For the continuous rating, we use a strategy for 0.9 kA analogous to the algorithms we have presented in the previous Section. Also, since continuous motor ratings are always specified without field weakening, we do not employ shunts. For maximum ratings we use the standard 1.25 kA strategy. A good agreement with literature is obtained for the continuous case, with the peak power as per our calculation being about 5200 HP. For the transient case however our maximum figure is greater than 6500 HP. This lack of agreement with the references may appear surprising; however the references' claims that a 40 percent increase in current causes a mere 6 percent increase in power are perhaps even more surprising.

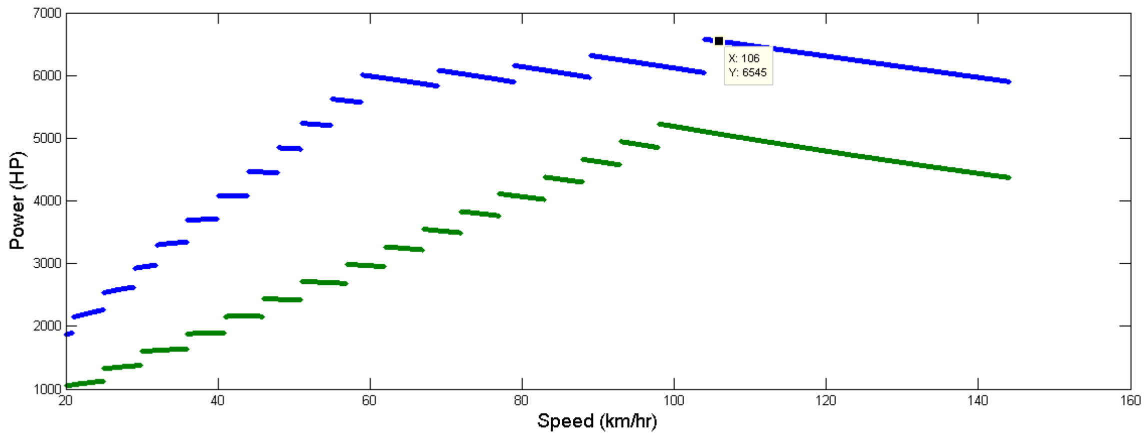

Figure 5 : *Mechanical power (in HP) developed by WAP4 as a function of speed. Green line corresponds to continuous ratings i.e. 0.9 kA in traction motor with no field weakening. Blue line is for 1.25 kA in motors with field weakening as necessary. The maximum value of 6550 HP on the blue line is noteworthy.*

With this we finally come to the conclusion of our discussion on the expected kinematic behaviour of a WAP4 if it is driven according to our algorithms.

B. Thermodynamics

It is known that the traction motor can withstand 1300 A for two minutes and 1100 A for ten minutes. How long will it tolerate 1200 A ? Moreover, the current during acceleration is not steady but fluctuates constantly. It can be 1250 A just after a notch/shunt transition and 1150 A or less just before a transition. The acceleration time can be considerable – with high currents it is four and half minutes for 21 high-drag LHB coaches from 30 to 130 km/hr. Can we be sure that in an attempt to save an extra minute, we are not pushing the motor beyond its limit ?

The importance of answering such questions is obvious; the way to answer them is to consider the thermal behaviour of the motor. Hence we now construct a model which can explain the heating of the motor when current is forced through it. We try to keep the model as simple as possible while remaining physically realistic. The crucial parameter which will determine whether a current-time combination is feasible or not is of course the temperature of the motor. We assume that there must be a maximum temperature which the motor can withstand; we shall obtain the value of this temperature from the model itself.

The thermal power generated inside the motor is on account of the current flowing through the various resistances, hence it can be written as αi^2 where α is a proportionality constant. The primary mechanism for cooling the motor is forced convection driven by the blowers; the rate at which heat is dissipated will increase with increasing difference between the motor temperature T and the surrounding temperature T_0. We assume Newton's law of cooling to hold and write the dissipated power as $\beta(T\text{-}T_0)$ where β is another proportionality constant. Finally, the increase/decrease in temperature of the motor is given by the ratio of heat generated/dissipated to its specific heat capacity C [no relation with the 'C' used in (5)]. Thus, over an instant of time Δt, the change in temperature ΔT of the motor is expressible as

$$C\Delta T = \alpha[i(t)]^2 \Delta t - \beta(T - T_0)\Delta t \quad . \tag{19}$$

Taking the obvious limit $\Delta t \rightarrow 0$ we get the differential equation for the temperature :

$$\frac{\mathrm{d}T}{\mathrm{d}t} + \frac{\beta}{C} T = \frac{\beta T_0 + \alpha[i(t)]^2}{C} \quad . \tag{20}$$

We let T_0=30°C as a typical value of atmospheric temperature. This still leaves two parameters β/C and α/C to be determined from known facts about the motor.

The first known fact is that the continuous current rating is 0.9 kA and that the temperature rating is 110°C. This at once implies that the heat generated by 0.9 kA must be equal to the heat dissipated by a temperature gradient of 80°C between the motor and its surroundings. In other words, taking i in units of kA,

$$0.81\alpha = 80\beta \quad , \tag{21}$$

or α/β=100. A second known fact must be invoked to find the second parameter. This fact is the maximum duration of the two current limits. The temperature of the motor after 1100 A for ten minutes must be equal to that after 1300 A for two minutes. This condition can be substituted into solutions of (20) after an assumption about the initial temperature. The natural choice for this temperature is the rated temperature of the motor – even after continuous rated operation one can operate it briefly in the transient mode.

Solutions to (20) with $i(t)$ constant are of the form

$$T = T_i \, \mathrm{e}^{-(\beta/C)t} + T_f \left(1 - \mathrm{e}^{-(\beta/C)t}\right) \quad , \tag{22}$$

where T_i is the initial temperature of the motor and

$$T_f = T_0 + \frac{\alpha i^2}{\beta} \quad , \tag{23}$$

is the final temperature of the motor in the steady state. Taking β/C in units of min^{-1}, we write the current duration criterion as

$$[30+100(1.69)]\left(1-e^{-2\beta/C}\right)+110\,e^{-2\beta/C} = [30+100(1.21)]\left(1-e^{-10\beta/C}\right)+110\,e^{-10\beta/C} \quad . \tag{24}$$

This transcendental equation is numerically solved to obtain β/C=0.285 whereby α/C becomes equal to 28.5 and all the parameters of (20) get determined. The tolerance temperature of the motor evaluates to 148°C. Now it is a straightforward matter to numerically solve (20) for the various acceleration runs depicted in Tables 3 and 4 and compute the final temperature of the motor. The initial condition for these runs must be specified and for safety, we must get an upper bound on the temperature before the acceleration run is commenced. A minimum gap of four minutes between successive acceleration runs is definitely plausible : 1.5 minutes coasting run, 1.5 minutes braking run and 1 minute of caution run. Hence, even if the preceding acceleration run drove the motor to its thermal limit, its temperature difference will have fallen by a factor of exp(-0.285x4) during this time (the power needed to sustain a caution run is negligible) and it will be at 70°C at the start of the next run. We work with this assumption on the initial condition. In Table 6 (the last Table in this Article, thank heaven) we present the temperature (in °C) of the motor at the end of the various acceleration runs described in Tables 3 and 4.

Speed range (km/hr)	Current (kA)	15 Load (740 ton)		18 Load (880 ton)		21 Load (1020 ton)	
		drag lo	drag hi	drag lo	drag hi	drag lo	drag hi
30-109	1.1	103	105	107	111	111	114
	1.25	109	113	115	119	121	123
30-119	1.1	106	109	110	115	115	119
	1.25	115	119	120	126	127	132
30-129	1.1	108	112	112	117	117	120
	1.25	119	124	125	132	131	138
30-139	1.1	114	119	118	125	124	132
	1.25	122	128	127	134	133	139

Table 6 : *Temperature (°C) attained by the motor after performing the 1.1 kA and 1.25 kA acceleration runs with various LHB loads (both drag formulae considered). The initial temperature is assumed as 70°C.*

Fortunately, none of the load combinations actually exceeds the motor's ratings. It can be seen however that there is a very high difference in the thermal burden of the 1.1 kA and 1.25 kA strategies. For the heaviest load, this can be almost 20°C. Though none of the temperatures in the Table is in the forbidden regime, the higher ones are quite close to the threshold and will surely cause increased wear and tear on the motor. Accordingly the 1.25 kA strategy, especially for heavy loads, should not be employed unless it is absolutely necessary. Of course, if a train is running late or its timetable in a particular section is very tight or the section contains a high number of caution orders, then the LP has to pull out all stops to recover/contain/minimize the delay. But in case of a train running right time through a reasonably slack section, the 1.1 kA strategies are sufficient. Tables 3-4 clearly show that the gain in time from the 1.25 kA strategies is only one minute or less and in such a situation the extra thermal load on the motors is not justified.

Having thus completed our discussion of the kinematic and thermodynamic behaviour of WAP4 hauling a train and being driven as per our algorithms, we promptly bring this Section to a close.

6. Concluding remarks

Relief is evident on the readers' faces at the mention of the word 'concluding'. Indeed, we have said all that we wanted to say. Every issue we could think of has been addressed, in as much detail as we have found necessary or relevant. Now we would like to wind up with a brief summary of what has been covered over the last twenty or so pages. For this purpose, we list below the major results of each Section in a more-or-less point form.

Section 1

- The motivation behind this study has been explained – our purpose is to ensure that the enormously capable loco called WAP4 be utilized to its full potential by its pilots.

Section 2

- Characteristic curves of the series dc motor with diverted field have been derived. Current and torque both decrease with increase in speed. The decrease can be offset by flux weakening.
- Equations (9) and (10) give the current speed and torque speed characteristics.

Section 3

- General strategies have been proposed for acceleration of tap changer controlled electric loco. At first, notches must be taken one after another with shunt set to zero. The rate of notching should be uniform in speed.
- When the maximum notch level is reached the shunts should be engaged provided that the current remains within its limit and there is a torque benefit.
- For holding train speed constant at MPS, determination of the balancing power is essential.

Section 4

- Strategies specific to WAP4 have been outlined, in a form appropriate for use by loco pilot on run. The algorithm is printed on page 17 of this Article.

Section 5

- Consequences of our algorithms have been discussed with focus on acceleration time and thermal burden on the motors.
- Two drag formulae for LHB trains have been used – one a theoretical expression (14b) from [14] and the other a modified expression (18) based on experiments. Acceleration times based on these formulae have been given in Tables 3 and 4 for a variety of loads.
- The maximum power output of WAP4 is found to be about 5200 HP for continuous rating and over 6500 HP for maximum rating.
- The increase in temperature of the motor on account of the acceleration runs has been computed and presented in Table 6. There is a marked difference between the heat burden of 1.1 kA and 1.25 kA strategies therefore the latter should be employed only when absolutely necessary.

We devote one last paragraph to the following issue : it is well known that the intuition and experience of a good loco pilot play a pivotal role in determining the performance of the train; does our scientific algorithm make these qualities redundant ? The answer to this is an emphatic no. Our strategies are meant to supplement and not supplant a dexterous LP's instincts. As we have already mentioned, the motor parameters can vary from loco to loco and a single strategy cannot account for a thousand parameter combinations. Our sheet is like an overall gameplan but the implementation of this plan will be specific to each loco. We can prescribe intervals ranging between 3.5 and 4.5 km/hr but the best value in any given situation will have to be determined live, in the cab. The better the LP, the better will he find this interval and the closer will he remain to the motor's permitted current. The same considerations hold for maintenance of MPS – we may mention typical balancing positions for certain loads but again the specific point has to be worked out by the LP on the run. That said however, our algorithms will go a long way in improving the performance of LPs on a daily basis. A less skilful LP will just have to follow the more conservative paths through our strategy sheets, such as taking the maximum intervals when a range has been specified. Still, the difference between his performance and the optimal performance will be quite small, unlike what happens now. Even skilled LPs have to accumulate a lot of experience before their instincts can take them close to the optimal strategy; our algorithm will give them a big headstart and enable them to clock good figures from their first day at the controls. Moreover, an LP driving by instinct is bound to show variation from one run to the next; this variation can be greatly reduced if the overall strategy is learnt like a formula and mechanically executed on run. Finally, a definite algorithm has enormous pedagogical advantages over instinctive methods; in driving schools, it can easily be imparted to the LPs during initial and/or refresher training.

Another paragraph has begun ! But this one is empty. Now this Article is really over and we would like to sincerely thank our readers for their patience in reaching this point.

* * * * *

References

[1] http://elocos.railnet.gov.in/Loco_bank/shedwise.aspx
[2] http://indiarailinfo.com/
[3] http://www.irfca.org/faq/faq-loco2e.html#wap-4
[4] http://www.railelectrica.com/traction-motor/dc-series-motor-as-traction-motor/
[5] A E Fitzgerald, C Kingsley and S D Umans, "*Electric Machinery*," Sixth Ed. Mc Graw Hill New York, USA (2008)
[6] D J Griffiths, "*Introduction to Electrodynamics*," Third Ed. Pearson Education, Saddle River, New Jersey, USA (2008)
[7] S Bhattacharjee, "*The Electromagnetism of the Induction Motor*," Lambert Academic Publishing, Saarbrucken, Germany (2013)
[8] S J Chapman, "*Electric Machinery Fundamentals*," Fourth Ed. Mc Graw Hill, New York, USA (2005)
[9] G V D A Kumar, S Kumar, R Mishra and N K Wadhonkar, "Stepper motor drive for onload tap changer in electric locomotive," Proc. Intl. Conf. Power Electronics, Drives and Energy Systems for Industrial Growth 2, 720-726 (1996)
[10] Electrical Engineering Directorate, Indian Railways, "Tips for better enginemanship for loco pilots."

http://www.indianrailways.gov.in/railwayboard/uploads/directorate/ele_engg/Circulars/TIPS_041011(1).pdf
[11] RDSO, "Pamphlet on Traction Motor HS 15250A," Gwalior, MP (2010).
http://www.rdso.indianrailways.gov.in/works/uploads/File/Pamphlet%20on%20Traction%20Motor%20HS-15250A-eng.pdf
[12] http://trainweb.org/railworld/Electric_Locos/wap4.htm
[13] http://www.cgglobal.com/frontend/ProductDetail.aspx?id=j7Cu6ITnQ60=
[14] http://www.railelectrica.com/traction-mechanics/train-grade-curve-and-acceleration-resistance-2/
[15] Ministry of Railways (Railway Board), "*Maintenance Manual for BG Coaches of LHB Design*," Gwalior, MP.
http://www.rdso.indianrailways.gov.in/works/uploads/File/Maintenance%20Manual%20for%20LHB%20Coaches(4).pdf
[16] RDSO, "Technical Circular No. ELRS/TC/0067-2000 (Rev '0')."
http://rdso.indianrailways.gov.in/works/uploads/File/TC_67.pdf

Appendix 1

A list of station codes used in the text is given below.

- ADI : Ahmedabad Junction
- ALD : Allahabad Junction
- ASR : Amritsar Junction
- BBS : Bhubaneswar
- BCT : Mumbai Central
- BDTS : Bandra Terminus (Mumbai)
- BRC : Vadodara Junction
- BSP : Bilaspur
- CNB : Kanpur Central
- CSTM : Chhatrapati Shivaji Terminus Mumbai
- DBRT : Dibrugarh Town
- DEE : Delhi Sarai Rohilla
- GZB : Ghaziabad Junction
- HWH : Howrah (Kolkata) Junction
- JU : Jodhpur Junction
- LJN : Lucknow Junction
- MAS : Chennai Central
- MGS : Mughal Sarai Junction
- NDLS : New Delhi
- NZM : Hazrat Nizamuddin (Delhi)
- RJPB : Rajendra Nagar Bihar (Patna)
- RNC : Ranchi Junction
- SDAH : Sealdah (Kolkata)
- TVC : Thiruvananthapuram Central
- YPR : Yesvantpur (Bengaluru)