Motor Re-Rating for Traction Applications – Field Weakening Revisited

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***Abstract* - The conventional wisdom in traction applications is to use machines in their field-weakening regime. Here, an alternative approach is given in which field weakening is avoided in an ac drive traction system. Instead, the motor's performance is extended through a reduced voltage re-rate procedure. This yields an extended full-flux regime that permits a given motor to achieve full rated torque and much higher power as its speed range is extended. Specific examples for electric vehicle drives are provided.**

I. Introduction

Long-established conventional wisdom in electric traction applications holds that motors should be used in their constant-power field weakening regime. This is probably based on two attributes of the field weakening regime: First, series-wound dc motors originally used for traction applications have a wide constant-power range, with very high stall torque and a sloped torque-speed characteristic that permits simple control. Second, the power level involved is based on nameplate rated maximum power, and logically the field weakening regime allows this power to be delivered at nearly any speed.

There are recent references that discuss the desire to have wide constant-power ranges for traction motors [1,2] and others that allude to the need to get the operating speed into the field weakening regime as soon as possible [3]. It is important to notice that [2], although pointing to a constant-power operating range, questions the value of field weakening. There it is proposed that the constant-power range (especially in a permanent magnet machine) be achieved at constant flux through reduction of current. Ref. [4] illustrates the challenge in a fuel-cell powered drive: power is limited by the bus voltage and available source current, rather than the motor per se. Field weakening becomes a strategy for managing the *source* rather than the system output.

A typical torque-speed capability curve for a high-cost permanent magnet motor intended for traction applications is given in Fig. 1 [5]. The constant power regime is about 3.5:1, as the motor rises above its base speed rating of 2200 RPM and reaches the maximum safe speed of about 7500 RPM. The efficiency contours in Fig. 1 suggest that this motor has been optimized for field weakening, since the best efficiency point is well into the weakening regime. The challenge of weakening the field in a permanent magnet machine is non-trivial. The general problem is considered difficult, and many current papers [6-9] consider methods for field weakening in permanent magnet machines.

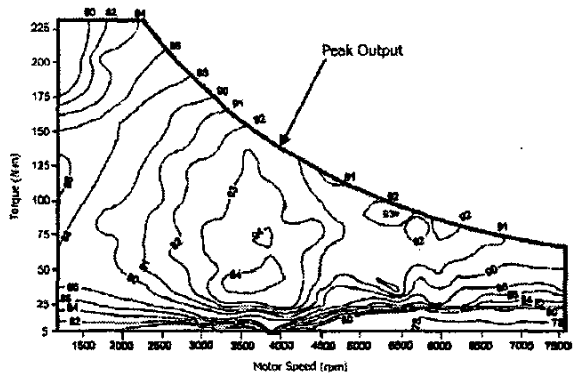

Fig. 1: Torque-speed characteristic and efficiency contours of a permanent-magnet ac motor with field weakening (from [5]).

The experience in our group directed at high-performance traction systems runs counter to the conventional wisdom. Our objective has been to minimize motor *mass*, while in much of the previous work the emphasis was on minimizing motor power [3]. We generally avoid the constant power operating regime, yet produce much higher power levels from smaller machines. At the same time, efficiency does not suffer. In comparative on-road tests of electric and hybrid vehicles [10], a non-weakened low-cost machine outperformed permanent magnet machines similar to the one represented in Fig. 1 by a wide margin. This achievement came about through a straightforward re-rating procedure. The idea itself is long established, but apparently is not usually considered to be an alternative to field weakening. In this paper we demonstrate that design choices intended to avoid field weakening offer dramatic enhancements to motor and system performance, much higher power per unit mass, and in general a low-cost alternative for high-performance traction. Through this method, a conventional 10 HP induction motor is being used as an equivalent 90 HP automotive traction motor -- at no extra cost.

II. Motor Re-Rating for High Power

A. Rating in terms of force

The size of any electromechanical device is related to the internal force it generates. In a magnetic machine, the force density is given by $\mathbf{J} \times \mathbf{B}$, with $\mathbf{J}$ as the current density vector

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and **B** as the magnetic flux density vector. In a rotating machine, the power produced is proportional to speed. It is simple enough to produce more power just by spinning the machine faster, as is the usual practice in aircraft. On this basis, it is important to recognize that the size and mass of a motor in a traction system are based on the target torque level. Motor output power is not directly related to size.

Once relegated to an inverter, the operating frequency rating of a machine loses its meaning. A conventional 50 Hz or 60 Hz machine supports a wide range of frequencies, limited mainly by extra core and eddy current losses as frequency increases. A motor of a given nameplate rating can be re-rated for alternative frequencies provided physical limits on current density and flux density are maintained. Since the flux in an ac machine is proportional to the voltage-to-frequency (V/f) ratio, a wide set of alternative ratings can be provided if the V/f ratio is held to a limit.

B. The Re-Rating Process

Consider a conventional 4-pole induction motor, rated by the manufacturer for 230 V or 460 V, three-phase, 60 Hz, and 10 HP. The rated torque of 40 N-m is determined by the current and flux in the machine. The possible continuous torque-speed capability under 460 V excitation is shown in Fig. 2. The torque can be maintained at the rated value up to the base speed of n = 1800 RPM. Above that level, rated voltage has been reached, and the field is weakened as $1/n$ to maintain rated voltage and current. The maximum continuous power is 10 HP (7.5 kW) above 1800 RPM.

Fig. 3 shows several capability curves for the same machine. Under a direct-drive scenario, rated torque can be maintained up to 6200 RPM, and the maximum power is 35 HP (26 kW). No ratings are being violated, no field is weakened, and the machine is identical! In a vehicle traction application, there is always a gear ratio between the motor and the drive shaft. If we alter the gear ratio by a factor of 3.45, a second capability curve results. In this case, the same machine with gearing provides an output of 138 N-m at speeds up to 1800 RPM. Then torque rolls off with conventional field weakening – at a power level of 35 HP.

Two other curves for typical gear ratios of 6:1 and 12:1 are also shown in Fig 3. Notice that the 12:1 ratio (which might represent a direct-drive requirement for a high-performance electric vehicle) could have been met with a 1:1 gear ratio and a motor rated for 480 N-m and a base speed of 150 RPM. Such a machine would have a mass twelve times that of the base 10 HP machine. Since gears will be present, the 12:1 ratio is much more practical.

The basis for the curves in Fig. 3 is a simple re-rating procedure. The motor has been wound in a conventional manner to support either 230 V or 460 V line input at nominal frequency. If all the basic winding leads are brought out to the terminals (a standard "twelve-lead" wiring configuration in place of the more usual "nine-lead" configuration), the motor can be wired for low-voltage or high-voltage input in either wye or delta connections. Notice that the nameplate voltage rating refers to both the flux rating (determined by voltage per unit frequency) and to the voltage capabilities of the insulation system. At 60 Hz, for example, we can operate at 460 V line-to-line, 60 Hz in a high-voltage wye configuration. No violation would occur by operating at 460 V line-to-line, 120 Hz in a low-voltage wye configuration. Table I shows the maximum speeds and other capabilities of this machine for its four connections.

None of the settings in Table I violates any ratings, provided the motor can be used safely at speeds as high as 6240 RPM. In effect, they simply extend the constant volts per hertz by providing a frequency range above 60 Hz over which a 460 V input supply can function. The motor is

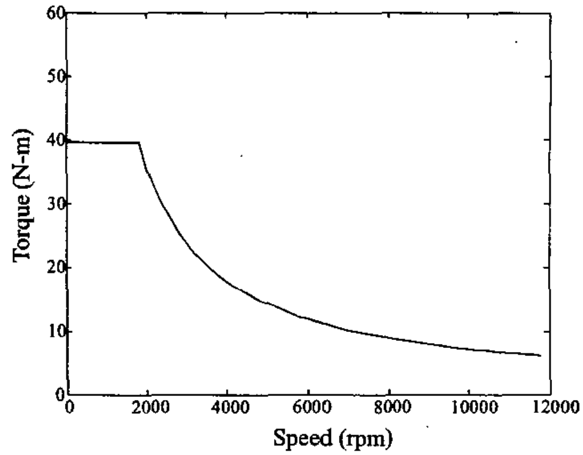

Fig. 2. Torque-speed characteristic of available 10 HP stock motor with field weakening above 1800 rpm.

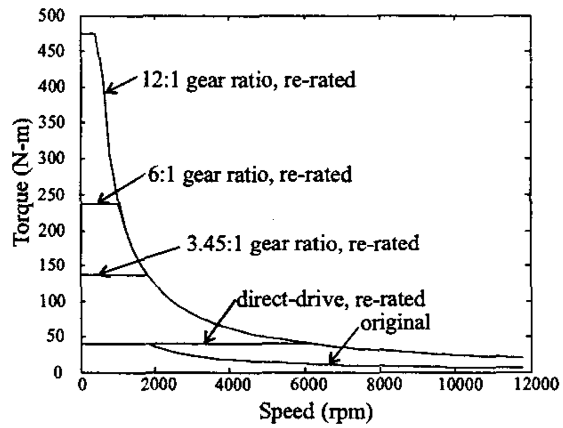

Fig. 3. Comparison of original motor configuration and re-rated configuration with several different gear ratios.

TABLE I: ALTERNATIVE POWER RATINGS FOR A DUAL 460/230 V, 60 HZ, 10 HP INDUCTION MACHINE.				
Connection	Freq. (Hz)	Base Speed (rpm)	Power at base speed (HP)	Torque (N-m)
High-voltage wye	60	1800	10	40
High-voltage delta	104	3120	17.3	40
Low-voltage wye	120	3600	20	40
Low-voltage delta	208	6240	34.6	40

considered as a source of torque, and extra power is provided simply by running the machine faster. As mentioned above, the practice is not new. Motors rated for 400 Hz have long been common in aircraft and marine applications, and achieve high output power with low mass by operating at high speed and high frequency. In [2], motor re-rating is used to reduce the base speed and extend the field weakening range to accommodate supply limitations.

The same procedure would apply to a permanent magnet synchronous machine (PMSM). Consider a machine intended for operation up to 100 Hz, 200 V three-phase RMS, 100 N·m rated torque, 6 poles, 2000 RPM base speed, 21 kW output, and a 3:1 field weakening range. If the stator winding taps are rearranged to provide a 66 V rating (low-voltage delta connection) instead, and a source capable of delivering 200 V at 300 Hz is available, this same machine can be re-rated for 300 Hz, 200 V, 100 N-m, 6000 RPM, and 63 kW output power without field weakening ratings violations.

III. APPLICATION

Modern electric traction applications are often characterized by a specific target dc bus voltage. The EV1 commercial electric vehicle [11] and also our prototype [10] use 312 V battery bus levels and induction motors for traction. With a PWM drive system that has 5% of third-harmonic compensation for overvoltage, a 312 V bus supports ac line-to-line potentials up to 232 V RMS. In our specific case (Fig. 4), we began with a motor that had been

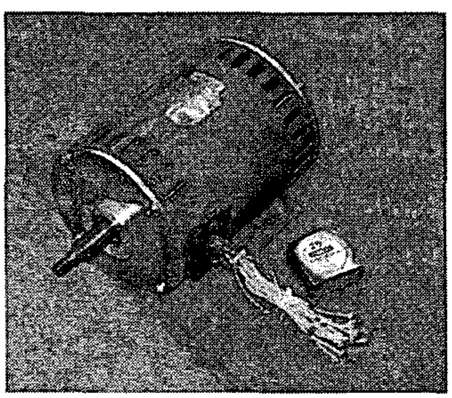

Fig. 4. Photograph of a stock 10 HP, 60 Hz induction motor that achieves a 90 HP automotive traction rating when re-rated.

TABLE II: ALTERNATIVE SHORT-TERM POWER RATINGS FOR DUAL 115/230 V, 60 HZ, 10 HP INDUCTION MACHINE (AT 232 V).				
Connection	Freq. (Hz)	Base Speed (rpm)	Short-term Power (HP)	Short-term Torque (N-m)
High-voltage wye	61	1815	25	103
High-voltage delta	105	3145	44	103
Low-voltage wye	121	3630	50	103
Low-voltage delta	210	6290	87	102

factory configured for a dual 115 V/ 230 V 60 Hz rating (a low-cost modification of winding taps compared to the catalog 230 V/ 460 V connections). The motor has continuous ratings of 10 HP, 88 A, 1745 RPM, and 41 N- m in the low-voltage delta connection at 60 Hz, and short-term ratings of 25 HP, 230 A, 1650 RPM, 103 N-m in this arrangement. However, since the bus supports up to 232 V RMS, the ultimate short-term rating is enhanced by a factor of 3.5 to 88 HP, 230 A, 210 Hz, 6150 RPM, 103 N-m. This does not take into account the extra service factor of 15% that pushes the short-term rating well above 90 HP. Table II shows the four winding connection ratings for this machine.

Notice that nothing has been lost in terms of performance: the torque capability below 1800 RPM has not changed at all, while that above 1800 RPM has increased. Field weakening is not needed until the new base speed of nearly 6300 RPM is reached, and at this new speed, a torque enhancement factor of 350% has been achieved in comparison to field weakening based on the stock nameplate values. All of this has been provided without violations of ratings. In effect, we have re-rated a multi-voltage 10 HP, 60 Hz motor as a low-voltage 200 Hz, 90 HP traction motor, and the extra bus voltage avoids the need for field weakening. The electronic drive needs have changed, however. The stock motor has a continuous current rating of 25 A in high-voltage wye connection (230 V, 60 Hz), compared to the continuous 88 A re-rating value. This means an electronic drive with higher current capability must be used. The effect is hardly a surprise: a 35 HP drive (with 250% short-term capacity) must be used instead of the original 10 HP drive, but in return we get continuous 35 HP capability from the machine.

A key question is that of how the efficiency has been affected by re-rating. The higher operating frequencies will lead to much different distributions of losses. It is important to keep in mind that the new frequency ranges are relatively modest (210 Hz compared to 60 Hz), so the loss effects can be characterized well. Table III lists some loss tradeoffs for a motor with a 350% re-rating factor (the change from high-voltage wye to low-voltage delta). At 60 Hz, the only loss change is in the inverter, but this is consistent with the need for a higher-power inverter. At 210 Hz, there are extra stator magnetic losses. These could have been managed through use of thinner stator laminations, but we have been working from a stock configuration.

The net effect in Table III is that at 60 Hz, 1800 RPM output the motor losses are identical in all connections, but

TABLE III: LOSSES AND OTHER CONSIDERATIONS.						
Connection	Stator iron loss	Copper loss	Windage loss	Rotor loss	Inverter loss	Power output
High-voltage wye, 60 Hz	Nominal	Nominal	Nominal	Nominal	Nominal	Nominal
High-voltage delta, 60 Hz	Nominal	Nominal	Nominal	Nominal	Higher	Nominal
Low-voltage wye, 210 Hz, with weakening	350%	10%	Higher	Lower	Nominal	Nominal
Low-voltage delta, 210 Hz	350%	Nominal	Higher	Nominal	Higher	350%

inverter losses are highest for the high-current low-voltage delta connection. A drive capable of full power will be needed. The effect at 210 Hz, 6290 RPM for the conventional field weakening case is that the output power rating is unchanged, and that lower copper losses approximately offset higher iron and windage losses to keep the efficiency about the same. With the re-rating procedure, iron losses and windage losses are higher but copper losses are nominal. The effect is that losses are higher (but by less than the factor of 3.5) while output power is also higher by a factor of 3.5. To first order, the efficiency at high output power is potentially higher in the re-rating case than in the nominal case.

This small machine -- a stock 10 HP unit -- has an automotive traction rating of 90 HP. Notice that the re-rating procedure has produced a substantial reduction in mass and volume for a given traction power requirement. Indeed, it appears that motor re-rating to avoid field weakening will always give a lower mass machine than the conventional method implied by Fig. 1. The mass reduction is important in vehicular and other mobile applications, since both space and weight concerns are paramount in these contexts.

How far can the process be taken? The EV1 has a rated motor speed of 15,000 RPM, and delivers 75 HP or more even though it is small. The motor of Fig. 4 provides a high-performance replacement for a 100 HP internal combustion engine – with air cooling. The drawback is higher current in low speed cases. This is not so much an issue in traction applications, since "rated power" is not a well-defined concept in these situations. The motor of Fig. 4, with its air cooling shroud and all mounts, has a mass of only about 36 kg, and delivers more than 1800 W/kg at peak output, yet it is a stock 10 HP induction motor.

Many workers have advocated a wide constant power range as a way to avoid a transmission in an electric traction application. However, the need for a gear ratio means that at least a "single-speed transmission" is in place. A special advantage of electric machines is the possibility of precise control. One can envision an "automatic gear box" that delivers the performance and efficiency of a simple multi-speed manual transmission with full automation of the gear shifting process. This was successfully implemented with our motor [12], and showed that the transmission does not impose cost or performance limitations.

IV. CONCLUSION

The mass and cost of the drive motor for traction applications can be reduced by re-rating the machine as opposed to field weakening. The process takes advantage of the wide frequency capability of an electronic drive to deliver full output torque over an extended speed range. A 350% increase in power output over the nameplate rating was achieved on a stock 10 HP, 60 Hz, induction machine without violating any ratings. The machine was able to replace an internal combustion engine, and provided high power to weight ratio in an inexpensive air-cooled system.

V. ACKNOWLEDGMENT

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