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Can a Small Voltage Increase be Used to Improve an Electric Motor's Efficiency?

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Can a small Voltage increase be used to improve an electric motor's efficiency?

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Introduction

I was both intrigued and challenged by a recent technical article that claimed that "*the efficiency of all electric motors can be greatly improved by increasing the supply voltage to the motors*". This change can in most instances easily be done by changing the tapings on the supply transformer.

I was intrigued because I've never seen any technical analysis on such a claim and I was challenged because I've never done such a study myself.

This paper looks are various real motors to investigate the effect on the motor's performance, efficiency and energy costs when the stator supply voltage is increased marginally.

Level of voltage increase

In most instances, the motor's supply voltage can easily be increased by 5%. This is because the upstream transformer for electric motors is normally fitted with an off-load tap changer, with tapings for -5%, -2.5%, 0%, +2.5 and +5% voltage change. Primary incoming transformers are normally fitted with a much wider on-load voltage range (-15 to +7.5% typically) but they normally feed not only motors, but the complete plant. It would be irresponsible to change the voltage for the whole plant.

Modelled Values

Unfortunately the data had to be obtained through extensive modelling, resulting in huge amounts of data. This full scope of this data is available from the author. The main performance values will be listed for different types of motors. None of the values should be interpreted to quantify the quality or reliability of the listed motors. The values should just be used in to investigate the validity of the statement that the efficiency of the electric motor population can be increased by increasing the supply voltage.

[1] *Energizer* is the Journal of the Institution of Certified Mechanical and Electrical Engineers and the Journal of South African Institute of Electrical Technician Engineer.

Although not mentioned by the original article on the increase of stator voltage improving the efficiency of all motors, the paper entitled "High Efficiency Motors: Fact or Fallacy?" as published in the April 2003 edition of the Vector magazine, the power factor of the motor cannot be discarded, since it may in fact play a much bigger role in the total energy cost of running the motor when compared to the motor's efficiency. (This paper is available on request from the author.)

Some assumptions had to be taken in the modelling of the designs. The comparative results are listed below.

Energy Costs

To put the "savings" into perspective, the direct energy costs as well as the cost for the maximum demand will be calculated using equations 1 and 2. A rate for the energy will be used as 23c/kWh and a rate of R50/kVA will be used for the maximum demand. The calculations will be annualised, assuming running times of firstly for a *light duty*, 12 hour per day, 5 days per week, and secondly for a *normal duty*, 24 hours per day, 7 days per week.

$$\text{Cost [R]} = \frac{\text{Mechanical Output Power [kW]}}{\text{Motor Efficiency [\%]/100}} * h * \frac{d}{365} * \text{Energy Cost [R/kWh]}$$

Equation 1: Calculation for the direct energy cost.

Where:
h = hours running per day
d = days running per year

$$\text{Cost [R]} = \frac{\text{Mechanical Output Power [kW]}}{\text{Motor Efficiency [\%]/100} * \text{PowerFactor}} * \text{Maximum Demand Rate [R/kVA]} * 12$$

Equation 2: Calculation for the maximum demand cost.

Details		Values			Unit	Values		
Manufacturer		Siemens				HSE		
User		Gold mine				Gold mine		
Driven load		Water pump				Unknown		
Poles		2				10		
Voltage		100%	105%	Change		100%	105%	Change
		6600	6930	+5%	V	6600	6930	+5%
	@ % load							
Output Power	100%	1100	1100		kW	300	300	
	75%	825	825			225	225	
Current	100%	106.48	101.76	-4%	A	37.16	36.57	-2%
	75%	80.11	77.10	-4%		30.54	30.65	+0%
Efficiency	100%	95.67%	96.79%	+1.12%		94.42%	94.33%	-0.09%
	75%	95.63%	95.67%	+0.04%		94.48%	94.25%	-0.23%
Power Factor	100%	0.944	0.941	-0.3%		0.747	0.724	-3.1%
	75%	0.942	0.935	-0.7%		0.681	0.65	-4.6%
Speed	100%	2976	2978	+0%	rpm	594	594	+0%
	75%	2982	2984	+0%		595	596	+0%
Termperature Rise	100%	69.7	65.9	-5%	°C	80.3	80.6	+0%
	75%	48.5	47.1	-3%		58	59.9	+3%
Full load torque		3530	3527	-0%	Nm	4826	4821	-0%
Starting torque	Un-saturated	0.53	0.56	+6%	pu	0.77	0.83	+8%
		1871	1975	+6%	Nm	3716	4002	+8%
	Saturated	0.75	0.79	+5%	pu	1.80	1.93	+7%
		2647	2786	+5%	Nm	8687	9305	+7%
Pull-out torque	Un-saturated	2.58	2.78	+8%	pu	2.41	2.62	+9%
		9107	9805	+8%	Nm	11631	12632	+9%
Starting current	Un-saturated	5.47	5.90	+8%	pu	4.55	4.80	+5%
		582	600	+3%	A	169	176	+4%
	Saturated	6.51	7.01	+8%	pu	6.72	7.07	+5%
		693	713	+3%	A	250	259	+4%
Flux density	Back of core	1.244	1.308	+5%	T	0.768	0.808	+5%
	Tooth	1.261	1.326	+5%		1.413	1.48	+5%
Energy Costs: Light duty	Energy	R 827 k	R 818 k	-1.2%		R 229 k	R 229 k	+0.1%
	Maximum damand	R 731 k	R 725 k	-0.8%		R 255 k	R 264 k	+3.3%
	Total	R 1,558 k	R 1,542 k	-1.0%		R 484 k	R 492 k	+1.8%
Energy Costs: Normal duty	Energy	R 2,317 k	R 2,290 k	-1.2%		R 640 k	R 641 k	+0.1%
	Maximum damand	R 731 k	R 725 k	-0.8%		R 255 k	R 264 k	+3.3%
	Total	R 3,047 k	R 3,014 k	-1.1%		R 895 k	R 904 k	+1.0%

Details		Values			Unit	Values		
Manufacturer		AEI				HSE		
User		Power Station				Uranium Mine		
Driven load		Fan				Fan		
Poles		2				4		
Voltage		**100%**	**105%**	**Change**		**100%**	**105%**	**Change**
		6600	6930	+5%	V	3300	3465	+5%
	@ % load							
Output Power	100%	2475	2475		kW	250	250	
	75%	1856.25	1856.25			187.5	187.5	
Current	100%	243.41	235.74	-3%	A	58.20	58.85	+1%
	75%	184.73	182.19	-1%		47.98	49.87	+4%
Efficiency	100%	96.30%	96.37%	+0.07%		94.03%	93.86%	-0.17%
	75%	96.35%	96.31%	-0.04%		93.81%	93.43%	-0.38%
Power Factor	100%	0.925	0.907	-1.9%		0.798	0.753	-5.6%
	75%	0.913	0.884	-3.2%		0.727	0.67	-7.8%
Speed	100%	2983	2984	+0%	rpm	1486	1487	+0%
	75%	2987	2989	+0%		1489	1490	+0%
Termperature Rise	100%	79.8	76.7	-4%	°C	79.6	82.0	+3%
	75%	53.0	52.9	-0%		57.2	61.6	+8%
Full load torque		7923	7919	-0%	Nm	1607	1606	-0%
Starting torque	Un-saturated	0.40	0.43	+8%	pu	1.31	1.46	+11%
		3169	3405	+7%	Nm	2105	2344	+11%
	Saturated	0.50	0.54	+8%	pu	1.78	2.00	+12%
		3962	4276	+8%	Nm	2860	3211	+12%
Pull-out torque	Un-saturated	2.57	2.80	+9%	pu	3.57	3.95	+11%
		20363	22174	+9%	Nm	5737	6342	+11%
Starting current	Un-saturated	5.48	5.72	+4%	pu	7.02	7.34	+5%
		1334	1348	+1%	A	409	432	+6%
	Saturated	6.10	6.38	+5%	pu	8.09	8.48	+5%
		1485	1504	+1%	A	471	499	+6%
Flux density	Back of core	0.939	0.984	+5%	T	1.358	1.440	+6%
	Tooth	1.328	1.391	+5%		2.306	2.396	+4%
Energy Costs: Light duty	Energy	R 1,849 k	R 1,848 k	-0.1%		R 191 k	R 192 k	+0.2%
	Maximum damand	R 1,667 k	R 1,699 k	+1.9%		R 200 k	R 212 k	+6.2%
	Total	R 3,516 k	R 3,547 k	+0.9%		R 391 k	R 404 k	+3.2%
Energy Costs: Normal duty	Energy	R 5,178 k	R 5,174 k	-0.1%		R 536 k	R 537 k	+0.2%
	Maximum damand	R 1,667 k	R 1,699 k	+1.9%		R 200 k	R 212 k	+6.2%
	Total	R 6,845 k	R 6,873 k	+0.4%		R 736 k	R 749 k	+1.8%

Details		Values			Unit	Values		
Manufacturer		Alstom				ABB		
User		Paper Mill				Platinum Mine		
Driven load		Unknown				Unkown		
Poles		6				4		
Voltage		100%	105%	Change		100%	105%	Change
		3300	3465	+5%	V	6600	6930	+5%
	@ % load							
Output Power	100%	400	400		kW	634	634	
	75%	300	300			475.5	475.5	
Current	100%	88.11	85.18	-3%	A	67.28	65.25	-3%
	75%	68.20	67.33	-1%		51.45	51.00	-1%
Efficiency	100%	94.96%	95.13%	+0.17%		95.87%	95.91%	#####
	75%	95.14%	95.13%	-0.01%		96.16%	96.07%	#####
Power Factor	100%	0.836	0.822	-1.7%		0.86	0.844	-1.9%
	75%	0.81	0.782	-3.5%		0.84	0.811	-3.5%
Speed	100%	989	990	+0%	rpm	1487	1488	+0%
	75%	992	993	+0%		1491	1492	+0%
Termperature Rise	100%	79.7	76.3	-4%	°C	80.9	78.8	-3%
	75%	54.1	54.1	+0%		51.5	52.2	+1%
Full load torque		3863	3859	-0%	Nm	4071	4068	-0%
Starting torque	Un-saturated	0.56	0.63	+13%	pu	0.50	0.54	+8%
		2163	2431	+12%	Nm	2035	2197	+8%
	Saturated	0.97	1.11	+14%	pu	1.30	1.37	+5%
		3747	4283	+14%	Nm	5292	5573	+5%
Pull-out torque	Un-saturated	1.97	2.19	+11%	pu	1.94	2.11	+9%
		7611	8451	+11%	Nm	7898	8583	+9%
Starting current	Un-saturated	4.07	4.47	+10%	pu	4.18	4.47	+7%
		359	381	+6%	A	281	292	+4%
	Saturated	5.30	5.85	+10%	pu	6.60	6.98	+6%
		467	498	+7%	A	444	455	+3%
Flux density	Back of core	1.454	1.533	+5%	T	1.721	1.808	+5%
	Tooth	1.725	1.818	+5%		1.741	1.828	+5%
Energy Costs: Light duty	Energy	R 303 k	R 303 k	-0.2%		R 476 k	R 476 k	-0.0%
	Maximum damand	R 302 k	R 307 k	+1.5%		R 461 k	R 470 k	+1.9%
	Total	R 605 k	R 609 k	+0.7%		R 937 k	R 946 k	+0.9%
Energy Costs: Normal duty	Energy	R 849 k	R 847 k	-0.2%		R 1,332 k	R 1,332 k	-0.0%
	Maximum damand	R 302 k	R 307 k	+1.5%		R 461 k	R 470 k	+1.9%
	Total	R 1,151 k	R 1,154 k	+0.3%		R 1,794 k	R 1,802 k	+0.4%

Details		Values			Unit
Manufacturer		GEC			
User		Power Station			
Driven load		Pump			
Poles		4			
Voltage		100%	105%	Change	
		11000	11550	+5%	V
	@ % load				
Output Power	100%	13000	13000		kW
	75%	9750	9750		
Current	100%	845.06	850.29	+1%	A
	75%	662.49	683.88	+3%	
Efficiency	100%	95.51%	95.49%	-0.02%	
	75%	94.83%	94.75%	-0.08%	
Power Factor	100%	0.844	0.804	-4.7%	
	75%	0.811	0.75	-7.5%	
Speed	100%	1494	1494	+0%	rpm
	75%	1496	1496	+0%	
Termperature Rise	100%	79.9	80.4	+1%	°C
	75%	60.2	62.1	+3%	
Full load torque		83099	83076	-0%	Nm
Starting torque	Un-saturated	0.34	0.36	+6%	pu
		28253	29907	+6%	Nm
	Saturated	0.60	0.65	+8%	pu
		49859	54000	+8%	Nm
Pull-out torque	Un-saturated	2.10	2.27	+8%	pu
		174507	188583	+8%	Nm
Starting current	Un-saturated	4.32	4.50	+4%	pu
		3651	3826	+5%	A
	Saturated	5.69	5.90	+4%	pu
		4808	5017	+4%	A
Flux density	Back of core	1.343	1.397	+4%	T
	Tooth	1.725	1.797	+4%	
Energy Costs: Light duty	Energy	R 9,794 k	R 9,796 k	+0.0%	
	Maximum damand	R 9,676 k	R 10,160 k	+5.0%	
	Total	R 19,470 k	R 19,956 k	+2.5%	
Energy Costs: Normal duty	Energy	R 27,424 k	R 27,429 k	+0.0%	
	Maximum damand	R 9,676 k	R 10,160 k	+5.0%	
	Total	R 37,100 k	R 37,589 k	+1.3%	

Influence on performance

In all but two of the models, the full load current decreased. These decreases ranged between 2 and 4%. These decreases can be significant due to the reduced losses on the supply cable and lines.

The efficiency at 100% load increased on 57% of the models by an average of 0.37%, but the efficiency at 75% load only increase on one of the models and only by 0.04%. It is extremely important to remember that most motors operate in the load range of 70 to 85% of full load.

Surprisingly the power factor decreased on all of the models at both modelled operating load conditions by between 0.3% and 6% with and an average of 2.9% at 100% load and between 1% and 8% with an average of 4.4% at 75% load.

The change in speed and torque are negligible.

A significant benefit in 71% of the models was a decrease in the stator winding temperature. This can lead to prolonged insulation life on the winding.

As expected, on all of the models the starting and pull-out torques increased. This would reduce run-up times and will in most (but not all) cases be of benefit.

On all of the models the starting current increased significantly. This can have severe consequences on the cabling, switch gear, protection, etc. Another problem, especially in *weak* installations, would be that the voltage drop during the starting cycle would drop even further at this 105% supply voltage, than during starting at the normal 100% voltage. This in turn would lead to a quadratic drop in the starting torque, which could in extreme cases lead to stall conditions.

The flux densities are of major concern. Naturally the flux density is fairly linear over a small change in voltage. The major problem is that on machines with already high flux densities, the core is driven further into saturation, which would drastically increase the core losses, leading to reduced efficiencies, higher temperature rises, etc.

Energy costs

Even with improved efficiencies, only one of the seven modelled motors actually produced an actual total energy cost saving with an increase in stator voltage. The huge influence of the maximum demand cost offset the small savings due to some increased efficiencies. Increased maximum demand could however be counter-acted by power factor correction, but this would again incur additional costs.

If the motors however operate at 75% load (as is typical) **none** of the motor's would see a reduction in total energy cost with an increase in the supply voltage of 5%.

Conclusion

Although this study is fairly limited in its scope, it does highlight that the general statement of "*the efficiency of all electric motors can be greatly improved by increasing the supply voltage to the motors*" is not true.

Care should be taken where experiences on a single motor is used as a general rule for a population of thousands of motors throughout the country. Experts in the specific application should be consulted when modifications to motors and operating conditions are considered.

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About the Author:

Henk de Swardt has a B. Sc. in Electrical and Electronic Engineering. He has more than eleven years of electric motors experience, both in the electric motor repair industry, as well as the electric motor manufacturing industry. He was employed for several years by the Largest OEM in South Africa. He also received specialized training in France on the designing of Electrical Motors. He is currently serving the Electric Motor industry at the Largest repairer of MV and HV motors in Africa. For a full C.V. visit http://www.qtime.co.za/CV_Main.html

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