The Physics of Armature-Reaction

Author: Phil Corso, PE

Company: Epsicon Inc.

Location: Boca Raton, Florida

Issue Date: 05-Jan-2007

Revision 4: 03-Mar-2010

Contents

1. Introduction

This paper has four goals that are listed below:

a) Describe *Armature-Reaction* more clearly than hath been presented heretofore (I love lawyer-speak.)
b) Dispel doubt, misinformation, and misunderstanding that have cropped up in related A-List topics.
c) Reduce animosity (just kidding) about questionable or ambiguous jargon.
d) Eliminate myths, misnomers, and omissions.

Adjectives describing *Armature-Reaction* are plentiful, some even inventive, but most miss the point! Here are some pairs that were culled from A-List and Off-List responses: adds-subtracts; additive-subtractive; augments-negates; crowded-expanded; decreases-increases; fights-gives up; overcomes-replaces; overtakes-replenishes; magnetize-demagnetize; support-oppose; strengthen-weaken; and swell-shrink. There have been and certainly will be others! Thus far, no-one has used adjectives such as: encourage; discourage; thwart; or tweak! I hope this paper will curtail (hmm, a synonym I hadn't noticed earlier) the seemingly growing list of adjectives.

2. Definitions: Official; Time-Proven; and Preferred [Ref A & B]

IEEE STD 100 defines Armature-Reaction as, "The magnetomotive force due to armature winding current." Seems rather sparse! Karapetoff's definition in 1911 was, "When carrying loads armature-current being a source of mmf (magneto-motive-force), modifies the flux created by the field-coils, thus influencing the performance of the machine." As for me, I prefer, "*Armature-current mmf reacts with the field-current mmf, altering the airgap mmf, which causes a change of the internal generated emf (electro-motive-force..*"

3. Synchronous Generator Armature-Reaction (General Theory) [Ref C & D]

Let's start with the basics for a <u>*generator connected to an isolated load*</u>. The generator has two magnetic structures, one is the stator which is fixed in space, and the other is the rotor which is driven by a prime-mover. They are separated by an annular space called the air-gap (regardless of coolant-medium actually used, for those ready to pounce). Each structure carries windings that are linked by a mutual flux crossing the air-gap, and as a result a generated-emf is produced in the stator. Current in the rotor field-coils produce a rotating magnetic-field called *field-flux*. Current in the stator-winding produces its own synchronously rotating magnetic-field called *armature-flux*. Two observations can be made: 1) each mmf has magnitude and direction; and 2) they exist independently of one another. When the two fluxes interact the *resultant air-gap flux* causes *a* change in *generated-emf*. Thus, because field-current is constant and stator-current the variable, then a*rmature-flux* is said to affect *field-flux*. This interaction is called *Armature-Reaction*!

Digressing for a moment… an analogy to the above is the ocean surf's undertow! While the surface current can be seen moving towards the beach an unseen undersea current is also moving, but in a direction away from the beach! When the currents combine the resultant-current speed and direction determine a swimmer's fate. The effects of undertow and Armature-Reaction are similar, differing only in dimensional units, that is, the former uses physical quantities and the latter magnetic quantities.

The unit-dimension for mmf is ampere-turns. When the statement "the field…opposes…aides… shrinks… etc" is made, it actually means an increase (or decrease) in air-gap ampere-turns. Thus, its mmf can be treated as a vector, i.e., having magnitude and direction which are strongly influenced by the nature of the load. For a *lagging-current* load, armature-mmf *subtracts* ampere-turns from the field-mmf, thus ***weakening*** air-gap flux! Conversely, for a *leading-current* load, armature-mmf *adds* ampere-turns to the field-mmf, thus ***strengthening*** air-gap flux! A seemingly complex process? Yes, but not if one thinks of the process as a chain reaction: armature-flux modifies field-flux; resulting in an air-gap flux change; changing generated-emf; culminating in a change of terminal-voltage; requiring corrective action by the Automatic Voltage Regulator (AVR)! In general, for cylindrical-rotor machines the modification appears as shift in pattern, while for salient-pole machines there is pattern distortion.

4. Armature-Reaction in Cylindrical-Rotor Generator [Ref E]

Consider the bipolar machine shown in Figure 4-1. Three magnetic-fluxes can be identified by their associated mmf vectors: Φa, the armature-mmf created by current in the armature (stator) winding; Φf, the field-mmf created by current in the field-coils; and Φr, the resultant air-gap flux! The first two, armature-mmf IaNa, and field-mmf IfNf, are in quadrature, so their vector sum produces the resultant air-gap mmf IrNr. Note the shift of the magnetic circuit's neutral plane! The degree of shift is proportional to armature-current magnitude and power-factor of the load, i.e., unity, lagging, or leading!

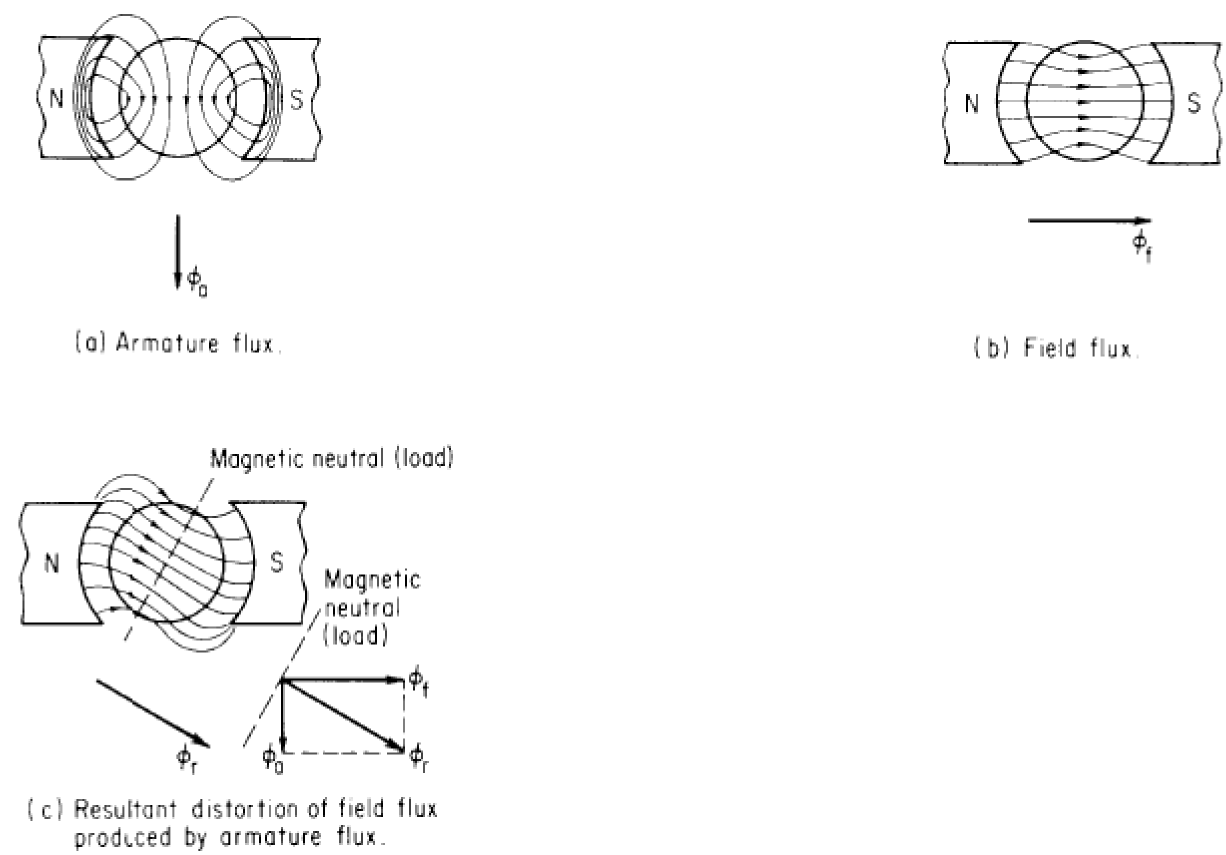

Figure 4-1: Air-gap flux Distribution in a Cylindrical-Rotor Machine

5. Armature-Reaction in a Salient-Pole Generator [Ref B & F]

Figure 5-1, shows how the resultant air-gap flux pattern is distorted and reduced in magnitude. As illustrated the resultant air-gap flux pattern is crowded toward the lagging tip of each field-pole. Why? Imagine the addition of two fictitious conductors **a'** and **b'**, whose currents are equal but opposite those in the actual conductors **a** and **b**, respectively. Thus, **a'-b'** mmf are canceled, and the armature-flux produced by the actual conductors **a** and **b**, remains unchanged. Now consider that **a-a'** form an ampere-turn, while **b-b'** form another. Note that the mmf of field-coil **a-a'** ***strengthens*** part of field-coil A's mmf, while the mmf of field-coil **b-b'** ***weakens*** part of field-coil B's mmf. The armature-current in **a-b** not only distorts the no-load field-flux, but it reduces the total-flux per pole. The method by which this occurs is described below!

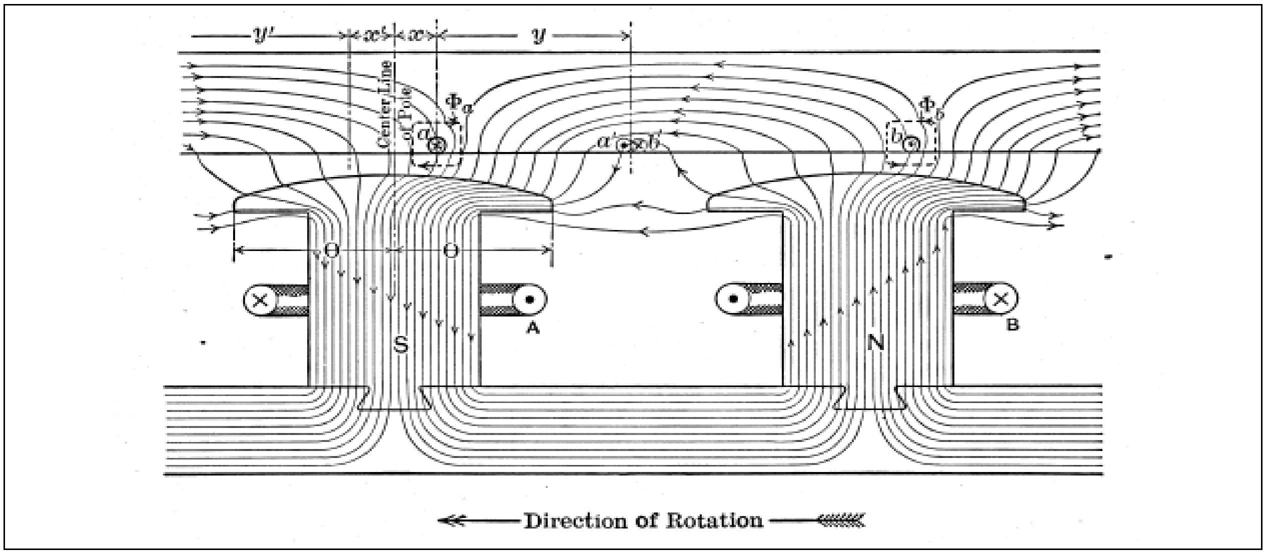

Figure 5-1: Flux Distribution of a Salient-Pole Machine

Consider the flux in four zones of the air-gap, as shown in Figure 5-1. They are tagged **x**, **y**, **x'** and **y'**, where **x** = **x'** and **y** = **y'**. The sum of the fluxes in zones **y** and **y'** is the same as without armature-current because the flux density in zone **y** is partly increased by the same amount by which it is reduced in zone **y'**. But in zones **x** an **x'** the flux is reduced by the armature-mmf, so that the total result over the pole-pitch is a reduction in the value of the no-load flux, as well as distortion! It can be shown that crowding of flux occurs at the pole-tip because the pole-tips are salient, meaning they protrude into the air-gap, making the reluctance along them variable.

Now that the *Armature-Reaction* process has been explained, and its units are in ampere-turns, then how does it influence a machine's electrical characteristics? The explanation is given in the next Section!

6. Armature Impedance∗, the Connection Between Magnetic and Electrical Circuits [Ref E, G, & H]

(All of the following parameters are expressed on a per-phase basis!)

It has been shown that the resultant air-gap flux is comprised of field-flux and armature-flux. Their corre-sponding emf's are Egp, Ef, and Ear, respectively. Thus, the generated-emf can now be expressed as the vector sum of terminal-voltage Vp plus a fictitious-emf proportional to Armature-Reaction flux called Ear, as shown in the following phasor equation:

Egp = Vp + Ear, where,

Egp is the generated-emf produced by the resultant air-gap flux and Vp, the terminal-voltage. Ear, is always in quadrature with, and proportional to, armature-current. It can be represented by an equivalent impedance voltage-drop IaZs, having a resistive and reactive component. The resistive component Ra, is the stator winding resistance, and the reactive component Xs, is the stator winding's synchronous reactance. The above equation for Egp, can be rewritten:

Egp = Vp + j(IaZs)

Furthermore, it can be shown that the synchronous reactance voltage-drop is comprised of two elements. The first IaXa, is the voltage-drop across the stator winding's leakage reactance. The second Ear, *inphase* with IaXa, is the Armature-Reaction mmf converted to an equivalent voltage. Expanding the equation above for Egp, yields:

Egp = Vp + IaRa + j(IaXa ± Ear)

∗ Note: when **Ra**, is very small compared to **Xs**, the term *Synchronous Reactance* is substituted for the term *Synchronous Impedance!*

7. Armature-Reaction is Affected by Nature of the Load, i.e., Lagging or Leading

[Ref D, E, and I]

As stated above the resultant air-gap flux develops the internal generated-emf. How then, are Armature-Reaction, generated-emf, and terminal-voltage related? The third equation, above, reveals that there are three factors that cause voltage-drops in a generator caused by: (1) armature resistance IaRa; (2) armature reactance-drop IaXa; and (3) Armature-Reaction voltage Ear. Armature resistance and reactance voltages will always reduce the terminal-voltage, but Armature-Reaction voltage may increase or decrease it depending on the load power-factor. And of course, all three voltages are directly proportional to load current.

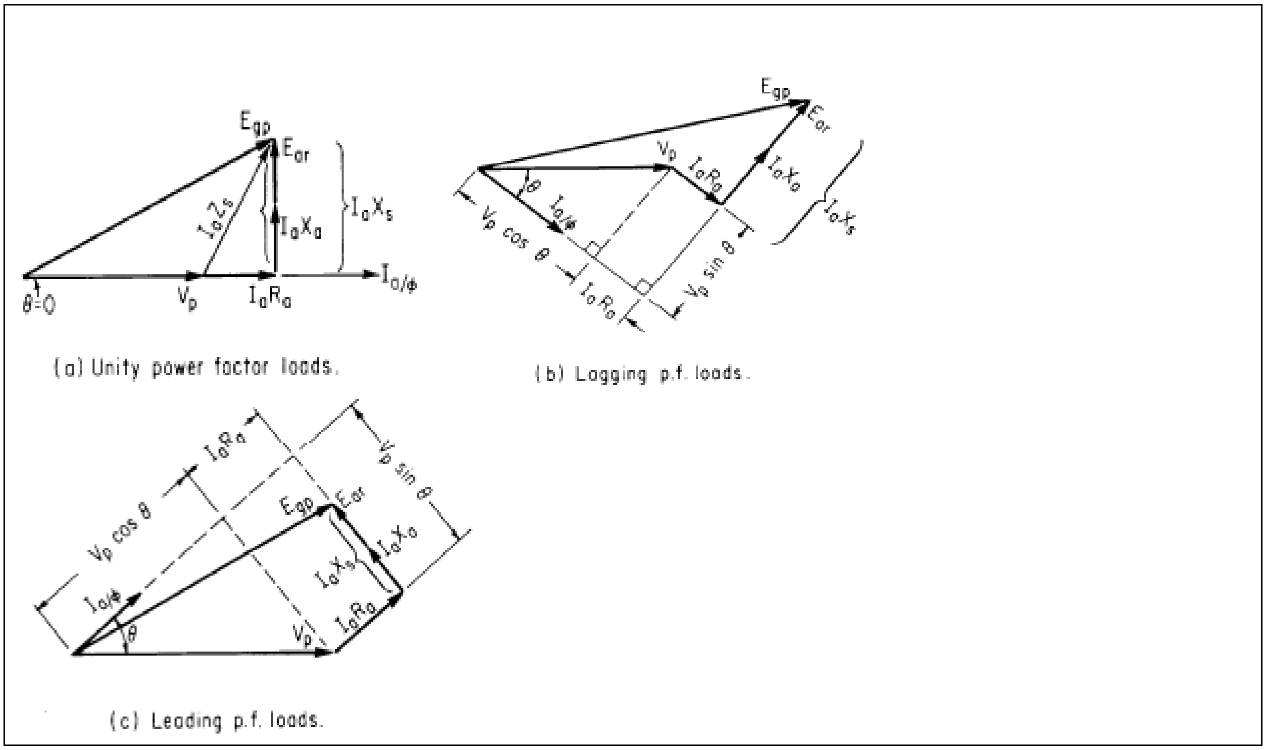

Figure 7-1: Simplified Vector Diagrams Illustrating Operation for Various Power-Factors

The vector relationship between the parameters shown in Figure 7-1, above, will now be examined in detail. Using the terminal-voltage Vp, as the reference vector, four cases will be considered**:** **(o)** no-load; **(a)** unity power-factor; **(b)** lagging power-factor; and **(c)** leading power-factor**.** The no-load case **(o)** is self-explanatory and doesn't need a diagram. The remaining three shown in Figure 7-1 illustrate the impact of power-factor. An analysis of each of the four conditions follows:

(o) No-Load. It can be seen in the no-load equation above that when the generator load is zero then, the terms containing armature-current drop-out. Thus, terminal-voltage and generated-emf are equal. The equation for this case is:

Egp = Vp

(a) Unity PF Load. This vector diagram shows that if armature-current Ia (by definition) is *inphase* with the terminal-voltage Vp, then the armature resistance voltage-drop IaRa, is in phase with Ia. The armature reactance voltage-drop IaXs, leads Ia, hence Vp, by 90°. The equation, which is simpler when presented in terms of horizontal and vertical components, is:

Egp = (Vp + IaRa) + j(IaXs), and for terminal-voltage the equation is,

$V_p = (E_{gp} - I_aR_a) - j(I_aX_s)$

(b) Lagging PF Load. This vector diagram shows that armature-current I_a (by definition) *lags* the terminal-voltage V_p, by the load power-factor angle θ°, but I_aR_a, is still *inphase* with I_a. Both the reactance voltage-drop I_aX_a, and Armature-Reaction voltage E_{ar}, *lead* armature-current I_a, by 90°. The equation, presented in terms of horizontal and vertical components, is:

$E_{gp} = [(V_p\cos\theta° + I_aR_a) + j(V_p\sin\theta° + I_aX_s)]$, and for terminal-voltage the equation is,

$V_p = [(E_{gp} - I_aR_a) - j(I_aX_s)] \div [\cos\theta° + j\sin\theta°]$

(c) Leading PF Load. This vector diagram shows that the armature-current I_a (by definition) *leads* the terminal-voltage V_p, by the load power-factor angle θ°, but I_aR_a, is still *inphase* with I_a. Both the reactance voltage-drop I_aX_a, and Armature-Reaction voltage E_{ar}, *lag* armature-current I_a, by 90°. The equation, also presented in terms of horizontal and vertical components, is:

$E_{gp} = [(V_p\cos\theta° + I_aR_a) + j(V_p\sin\theta° - I_aX_s)]$, and for terminal-voltage the equation is,

$V_p = [(E_{gp} - I_aR_a) + jI_aX_s)] \div [\cos\theta° + j\sin\theta]$

8. Conclusions.

Assuming that terminal-voltage V_p, is constant, then the effects of load power-factor on Armature-Reaction can now summarized:

- **Unity Power-Factor Load**.
  A unity power-factor load, defined as line-current *inphase* with terminal-voltage, causes armature-flux to ***weaken*** the air-gap flux produced by the field-coil alone! Field-current (excitation) must be *increased* to maintain terminal-voltage! (Note: if connected to other sources identified as an infinite-bus system, then the machine is said to *deliver or export* only kW!)

- **Lagging Power-Factor Load.**
  A lagging power-factor load, defined as line-current *lagging* terminal-voltage, causes armature-flux to ***weaken*** the air-gap flux produced by the field-coil alone! Field-current (excitation) must be *increased* to maintain terminal-voltage! (Note: if connected to other sources identified as an infinite-bus system, then the machine is said to be over-excited, and it *delivers or exports* lagging kVAr!)

- **Leading Power-Factor Load.**
  A leading power-factor load, defined as line-current *leading* terminal-voltage, causes armature-flux to ***strengthen*** the air-gap flux produced by the field-coil alone! Field-current (excitation) must be *decreased* to maintain terminal-voltage! (Note: if connected to other sources identified as infinite-bus system, then the machine is said to be under-excited, and it *delivers or exports* leading kVAr!)

The effects noted above are presented in Table 9.1 of Section 9, "Calculations Illustrating the Effect of Armature-Reaction on Generator Performance" for only the *isolated generator case!* Four operating modes are considered: a) no-load or when load current is zero; b) load current operating with a unity power-factor; c) load current operating with a lagging power-factor; and d) load-current operating with a leading power-factor!

9. Calculations Illustrating the Effect of Armature-Reaction on Generator Performance [Ref E]

Consider a 1,000-kVA 4,160-Volt, three-phase generator, having an armature resistance R_a, equal to 0.2 ohm per phase, and a synchronous reactance X_s, equal to 20 ohms per phase. Using the equations developed earlier, Table 9.1, below, illustrates the relationship between generated phase-to-neutral voltage E_{gp}, and the per-unit field-excitation voltage E_e. Six operational conditions are illustrated: no-load; unity power-factor load; two lagging power-factor loads, 0.75 and 0.4 pf; and two leading power-factor loads, 0.75 and 0.4 pf.

Table 9.1: Load Effect on Armature-Reaction

Constraints:	**Constant kVA**					
	Constant Vp					
kVA	**V_{pp}**	**Amps**	**Hz**	**Rpm**		
1,000	4,160	139	60	3,600		
Phase-to-Neutral	**V_{pn}**	**Ra, Ω**	**Xs, Ω**	**# Poles**		
Parameters	2,400	2.0	20.0	2		
Case	**1**	**2**	**3**	**4**	**5**	**6**
Load Type	**No-load**	**Unity**	**Lagging**		**Leading**	
Cos θ	-	1.00	0.75	0.40	0.75	0.40
Sin θ	-	0.00	0.66	0.92	-0.66	-0.92
kW	0	1,000	750	400	750	400
kVAr	0	0	661	917	-661	-917
Ia, Amp	0	139	139	139	139	139
$I_a \cdot R_a$, V	0	278	278	278	278	278
$I_a \cdot X_s$, V	0	2,780	2,780	2,780	2,780	2,780
$\|E_{gp}\|$ Volts	2,400	3,860	4,830	5,130	2,390	1,370
Excitation, per unit	1.00	1.61	2.01	2.14	1.00	0.57

10. Addressing Incorrect A-List Responses Related to Armature-Reaction.

Several A-List posters have advanced theories about Armature-Reaction that are wrong or confusing. Some fellow posters introduced myths; others mis-name the process of kVAr exchange between a generator and another power source or system; still others, have used incorrect unit-dimensions of electrical parameters. Lastly, I also omitted an important observation related to end-connection effects. Following are my comments concerning the most noteworthy discrepancies:

- **Armature-Reaction causes a change in field-current!**
  I am sure that what the A-List contributor observed was the corrective action of the AVR responding to the terminal-voltage change!

- **Armature-Reaction under-excites or over-excites the field!**
  IEEE Standard 100 does not define the terms *under-excite* or *over-excite*. Neither are there definitions for *over-excitation* and *under-excitation*. However, the research done for this paper indicates that, except for synchronous condensers, the terms under-excite and over-excite are in discussions related to interconnected generators, such as those operating in parallel, or those connected to an infinite-bus. In addition, the terms are used more frequently describing synchronous motor operation than for synchronous generator operation!

- **Armature-Reaction causes the field-flux to modify armature-flux!**
  Just the reverse is true. Field-flux is fixed, but armature-flux is proportional to armature-current. Therefore, it is <u>armature-flux that combines with field-flux resulting in a modified air-gap flux</u>!

- **Operation in parallel with other sources!**
  In my opinion a synchronous generator does not absorb, or consume, or import, or receive, or take-in, or produce, reactive power. Then, for consistency, the author suggests that the terms listed above, as well as reactive power, be eliminated. Instead, the expression that the generator ***delivers (***or ***exports)*** lagging or kVAr, and ***receives*** (or ***imports***) leading kVAr should be substituted! ***(<u>NOTE: this recommendation does not preclude anyone from using terms with which they are familiar</u>!)***

- **This one is mea culpa!**
  My response to the thread "*Alternator Running in Leading kVAr*" addressed the fact that low-pf *leading* current operation is more deleterious for armature end-connections than low-pf *lagging* current operation. I presented (correctly) the fact that increased stator-current results in a dangerous increase in stator conductor length. However, *<u>I failed to include a crucial point</u>*, which was, the heat present in the armature winding end-connection is disproportionately higher than that portion embedded in the stator slot, because their radiating surfaces are different, as well as the manner in which they are cooled!

- **Terminology… which unit-dimension is to be used? KVAR; KVAr; kVAR; or kVAr?**
  - Using SI-Units and multiples and prefixes for SI-Units, then kVAr is the correct term to use!
  - To overcome the problem when inductive kVAr and capacitive kVAr are in the same discussion, I suggest the use of terms kVAr(i) and kVAr(c), respectively!
  - The letter 's' often used to denote the plural of a particular dimensional unit, should be dropped.

- Finally, an aside. SI-Units were *approved by the US Congress in 1866*! However, stubbornness and ego (sound familiar?) on the part of our scientific, engineering, and technical communities prevent general acceptance in the USA!

11. Related Control.com List Topics

[a] www.control.com/thread/1026185377: 11-Nov-03; k*W and kVAr Sharing.*

[b] www.control.com/thread/1026218078: 09-Jan-06; *Effect of Leading MVAr in the Grid.*

[c] www.control.com/thread/1026220640: 26-Mar-06; *Reverse Reactive Power.*

[d] www.control.com/thread/1026221273: 11-Apr-06; *Alternator Running in Leading kVAr.*

[e] www.control.com/thread/1026224575: 04-Apr-06; *Gas-Turbine Synchronization.*

[f] www.control.com/thread/1026226787: 29-Sep-06; *Fluctuating on MW (Hunting.)*

[g] www.control.com/thread/1026227171: 09-Oct-06; *Armature-Reaction in Leading Power-Factor.*

[h] www.control.com/thread/1026227967: 02-Nov-06; *The Physics of… Armature-Reaction.*

[i] www.control.com/thread/1026228749: 29-Sep-06; *Fluctuating (Hunting) on MW.*

[j] www.control.com/thread/1026228749: 18-Nov-06; *Turbo-Generator Operation.*

[k] www.control.com/thread/1026229024: 27-Nov-06; *Reverse Active Power, leading MVAr.*

[l] www.control.com/thread/1026230100: 05-Jan-07; *Excitation Loss vs Inadvertent Energization.*

[m] www.control.com/thread/1026236301: 19-Jun-07; *Clarification of T-G Speed Control*.

[n] www.control.com/thread/1026236550: 25-Jun-07; *The Physics of.… Electrical Power.*

[o] www.control.com/thread/1026238188: 13-Aug-07; *Reactive Power (Part II).*

[p] www.control.com/thread/1026242714: 06-Jan-08; *Tie-Line Operation.*

[q] www.control.com/thread/1026244991: 03-Apr-07; *Generator MVAr*.

[r] www.control.com/thread/1026246449: 22-May-08; *The Physics of.… Power Transmission*.

[s] www.control.com/thread/1026249081: 10-Aug-08; *What Increases Generator Load.*

[q] www.control.com/thread/12504 83614: 17-Aug-08; *Importance or Reactive Power*.

12. List of References

[A] IEEE STD 100-1992, *The Standard Dictionary of Electrical and Electronic Terms*, I.E.E.E., 1993.

[B] Karapetoff, V., *The Magnetic Circuit*, McGraw-Hill Book Company, N.Y., 1911.

[C] Fink and Carroll, *Standard Handbook for Electrical Engineers*, 10^{th} Ed., McGraw-Hill Book Co.

[D] Gray, A., *Electrical Machine Design*, McGraw-Hill Book Company, N.Y., 1926.

[E] Kosow, I.L., *Electric Machinery and Control*, Prentice-Hall Inc., 1964.

[F] Liwschitz-Garik, M., *Electric Machinery (Vol II)*, D. Van Nostrand Company, Inc., N.Y., 1946.

[G] Say, M.G., *The Performance and Design of A.C. Machinery*, Pitman Publishing Corp., N.Y., 1958.

[H] El-Hawary, M.E., *Electrical Power Systems*, Prentice-Hall Inc, 1983.

[I] Lister, E., *Electrical Circuits and Machines*, McGraw-Hill Book Company, N.Y., 1960.