Motor Mythbusters: Torque-producing Force

by Peter Schimpf, P.E.

In describing how motor torque is developed, many textbooks incorrectly identify that the entire electromagnetic torque-producing force acts directly on the conductor.   This is true only for simplified devices where the conductor is located in the airgap. But this is not true for most modern industrial motors where the conductors are located within slots in the iron core (for example induction motor rotors and stators). When conductors are located in slots, the electromagnetic torque-producing forces act primarily on the iron core. There is some electromagnetic force acting on the conductors within slots, but it is primarily in the radial direction, rather than the tangential (torque-producing) direction.

The "Long Version"

I have written a "Long Version" discussion of this same topic here:
http://home.comcast.net/~electricpete1/torque_web/attach/LinkToTheLongVersion.htm
http://electricpete1.tripod.com/torque_web/attach/LinkToTheLongVersion.htm

The long version provides a detailed proof of these conclusions. I call it the "Long Version" because it is 60 pages long.   I can imagine that some readers would find reading 60 pages of my mathematically-oriented discussion only slightly more interesting than watching paint dry.   So, you are welcome to read the long version, but my feelings won't be hurt if you don't. For this shorter article, I will use a question-and-answer format to provide an overview of the subject and to address some of the likely questions.

Why is it important?

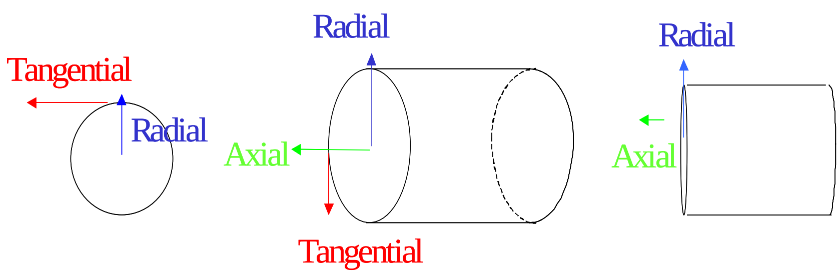
As professionals working with electric motors on a routine basis, we would like to think that we have an idea of how a motor actually works, including the basic function of producing torque. Knowing what forces actually do and don't act on the conductors is important in motor design and post-mortem analysis of failed motors.

On the lighter side, if you mention at a gathering of motor professionals that the electromagnetic torque-producing force in industrial motors acts primarily on the iron core (rather than the copper conductors), I can almost guarantee that it will generate a lively discussion.   In my experience, most people will react as if you had stated the earth is flat! The myth that the torque-producing force acts entirely on the conductors is very widespread.

What are the terms "tangential" and "radial"?

These terms are defined in Figure 1. Torque-producing force acts in the tangential direction.

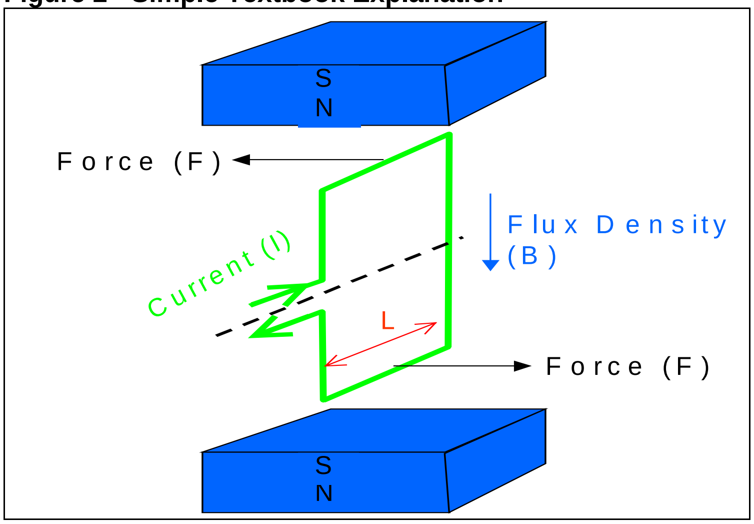
Figure 1 - Terminology for directions



What is the simple textbook explanation?

Figure 2 shows a typical simplified textbook explanation of the mechanism for producing torque in a motor. The figure includes permanent magnets to suggest the presence of flux. The current-carrying conductor is shown directly in the path of the magnetic flux. The force is given by the familiar equation F = L I x B, and the right-hand rule tells us the direction of electromagnetic force (thumb in direction of current, forefinger in direction of flux, and middle finger in direction of force[1]). The equal and opposite forces on the two legs of the current loop result in a torque.

Figure 2 - Simple Textbook Explanation

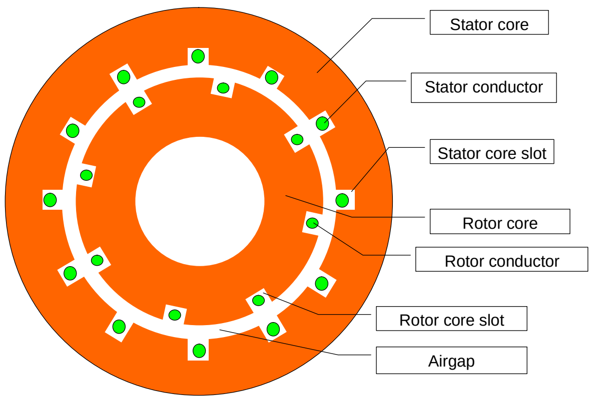


[1] The right-hand rule as described above is based on the "+ to -" current convention.

What's wrong with the simple textbook explanation?

There are in fact many devices like Figure 2 with the conductor located in free air directly in the main flux (for example an induction cup relay), and the figure correctly represents **those** devices in regard to the mechanism of force generation.

But an induction motor does not have conductors in free air in the main flux. An induction motor has conductors located in slots within an iron core[2], as shown in the following diagram:



What difference does it make if the conductors are located in slots?

Putting the conductor into slots surrounded by iron dramatically changes the flux pattern.

Figure 3 shows the flux pattern associated with a slot in the core adjacent to the airgap under no-load conditions. The flux takes the path of least resistance, which is generally the shortest distance traveled outside the iron, and very little flux flows directly through the slot.

Figure 4 shows the flux pattern when we have added current flowing in the conductor within the slot[3]. The current within the slot is flowing into the page, and by the right-hand-rule-for-direction-of-flux (thumb in direction of current, fingers in direction of flux) it creates a flux which encircles the current in the clockwise direction. This opposes the exciting flux on the left-hand side of the airgap and adds to the exciting flux on the right-hand side of the airgap, as can be seen by the fact that the flux density becomes higher on the right side (flux lines are closer together). A small amount of flux encircles a portion of the current by cutting across the slot in the tangential direction (horizontally to the right in this figure). This is known as the cross-slot flux.

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[2] The discussion of this paper refers to the portion of the conductor within the slots. There are also portions of conductors outside slots (vent ducts and end regions of rotor and stator) where the flux patterns and behavior are different, but these regions don't contribute much of the total motor torque

[3] The flux plots in this paper are based on finite element solutions for vector magnetic potential of a simplified geometry. The rotor current magnitudes are exaggerated for illustration. The model includes the rotor slots/current and stator exciting current. Stator slotting and stator load current are not modeled, but would not change the qualitative conclusions. Flux plots from other authors are available for comparison in the "Long Version".

In Figure 4 the radial (vertical) flux density (B) in the slot is much lower than in the airgap. Therefore using the relationship F= L I x B, we know that this current-carrying conductor in the slot will see much less torque-producing force than it would if it were in the airgap.

Figure 3 - Flux pattern for slot (no current)

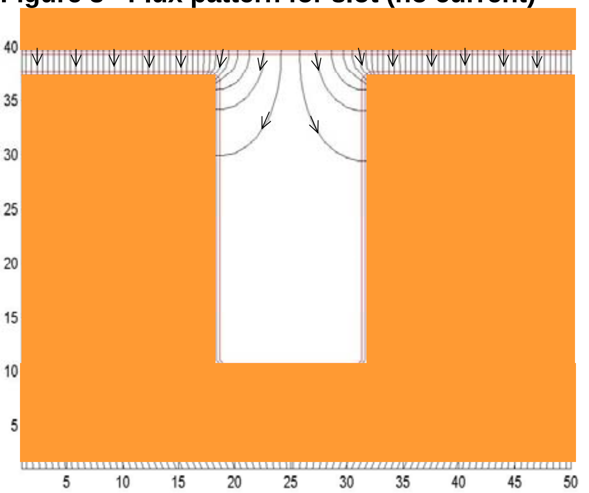
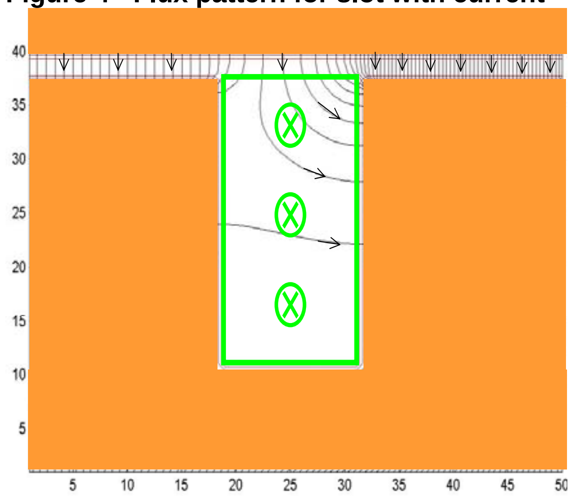


Figure 4 - Flux pattern for slot with current[4]



Why would we ever put conductors in slots, if it substantially reduced the torque-producing force on the conductor?

The conductors are put into slots primarily to protect the conductor insulation and to allow substantial reduction in the airgap depth and resulting reduction in the exciting current in induction motors.

But there is no penalty in terms of motor torque. While moving the conductors from the airgap into slots does reduce the electromagnetic torque-producing force acting directly **on the conductor** (for a given airgap flux and conductor current), it does not change the **total** electromagnetic torque producing force. What changes is where that force acts – on the iron core or copper conductor. The torque-producing force acts on the conductor when the conductors are in the airgap, whereas the torque-producing force acts primarily on the iron core when the conductors are in slots. But again, the total force remains the same for both cases if the current and airgap flux density remain the same.

Why does the total torque-producing force remain the same when I move the conductor from the airgap into the slot?[5]

That's not an easy question to answer. At first glance, there is no obvious reason why the total electromagnetic torque-producing force should remain the same. But a mathematical proof of the conclusion that it does remain the same[5] is included in the "Long Version", sections 8, 9, and 10.

On an intuitive level, if we examine the discussion of section 10 of the "Long Version", we notice a similarity of the airgap flux patterns produced by conductors in slots and conductors in the airgap. In particular, the flux pattern produced in the airgap on each side

[4] The symbol ⊗ indicates current direction into the paper.
[5] Assumes no change in airgap flux density or current when the conductor is moved between airgap and slot.

of a conductor located in a slot is identical to the flux pattern produced in the airgap on each side of a conductor within the airgap. Since the torque is transferred across the airgap by electromagnetic field action, we should suspect that the torque transferred depends on the flux pattern (and indeed Maxwell Stress Tensor theory confirms that it does). Therefore, it is reasonable to expect that similar airgap flux patterns resulting from conductors in slots and conductors in the airgap would give similar torques crossing the airgap.

What proof is there that the torque-producing force acts primarily on the iron core?

The proof is provided in the "Long Version", sections 11, 12 and 13. Here is an outline of the four-part proof of section 12:
#1 - Tconductor = R* N *I* L* Bslot* p.f.
#2 - Tmotor = R* N *I* L* Bgap* p.f.
#3 - Bslot << Bgap ("<<" means much less than)
#4 - Combining 1 thru 3 proves Tconductor << Tmotor.
where:

- N = number of conductors
- L = length of each conductor in the slot section
- I = rms value of the fundamental current in each conductor
- Bslot is rms of the fundamental radial flux density in the slot section
- Bgap is rms of the fundamental radial flux density in the airgap
- p.f. is cosine of angle between B and I which represents a power factor
- Tmotor = motor torque (sum of conductor torque and iron torque)
- Tconductor = torque created by force acting directly on the electrical conductors
- R = radius (from center of motor to the airgap, or to the conductor – assumed approximately the same)

I will provide a little more discussion on each of these four items.

#1 follows in a straightforward manner from the familiar expression for force on a conductor: F= L I x B. The detailed derivation of #1 is provided in the "Long Version", subsection 12.3.

#2 has the same form as #1, except for the choice of flux density B (#2 uses Bslot vs. Bgap). This follows from the fact that the total torque on the motor is the same as we would see if the conductor were located in the airgap, so we can derive equation #2 in the same manner as equation #1 except using flux density Bgap. #2 is consistent with textbook expressions for total motor torque ("Long Version" subsection 12.4.2) and has been used to correctly predict total motor torque on example motors ("Long Version" subsection 12.4.1) .

#3 (Bslot << Bgap) follows very intuitively from the fact that the flux follows the path of least resistance which is the shortest distance outside the iron. This is shown in figures Figure 3 and Figure 4 above, and is confirmed through numerous references identified in subsection 12.5 of "The Long Version".

#4 combines the previous three items together using simple algebra to demonstrate the conclusion Tconductor << Tmotor and the majority of the torque acts on the iron:

- #1/#2 = Tconductor/Tmotor = (R N L I Bslot pf) / (R N L I Bgap pf) = Bslot/Bgap
- Tconductor/Tmotor = Bslot/Bgap
- If Bslot<<Bgap (#3), then Tconductor<<Tmotor
- And of course, since only a small fraction of the total motor torque acts on the copper conductor, the remainder of the torque (which is the majority of the torque) must act directly on the iron core.

Can you explain how the torque-producing force acts on the iron core?

The basic principle is that iron is attracted towards an area of higher magnetic flux density. We have all seen this by holding a paper clip next to a permanent magnet: the steel/iron paper clip is *attracted toward the region of higher flux density* area created by the permanent magnet.

This principle may also be familiar to readers when studying the effects of magnetic pull on a rotor that is off-center within the airgap. Consider a 2-pole motor at a snapshot in time when the stator exciting field creates a North pole on top of the airgap and a South pole on bottom. In Figure 5, with the rotor centered, the flux density is the same on top and bottom, so the upward force on the rotor created by the flux density on top is cancelled by the downward force on the rotor created by the flux density on bottom and the net radial force on the rotor is zero. But in Figure 6 with the rotor closer to the top, the flux density becomes higher on top of the rotor and lower on bottom[6]. This results in higher force density on top of the rotor than on bottom, which results in a *net force pulling the rotor upwards towards the region of higher flux density*.[7]

Figure 5 - Rotor centered in airgap (no net force)

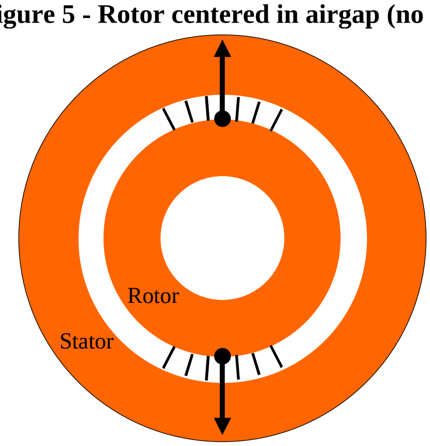
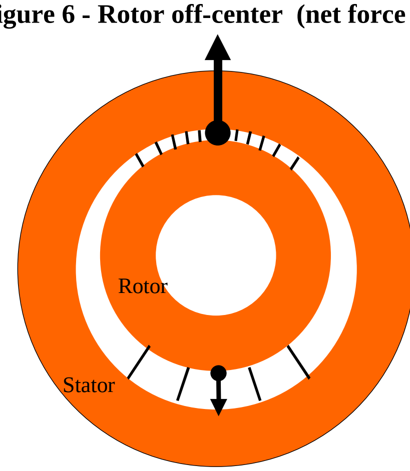


Figure 6 - Rotor off-center (net force upward)



[6] Figure 6 assumes that there is a low-reluctance path for homopolar flux.
[7] This is a mechanism for increased twice line frequency vibration in the presence of static eccentricity.

Now let's apply the same principle to the core tooth shown in the center (between the two slots) in Figure 7. The core tooth has flux lines penetrating on the left side, the right side, and the top. The flux on the top of the tooth would create an upward force as shown in Figure 8, which is the same type of force (radial) that was discussed previously in connection with Figure 5 and Figure 6, but this upward force does not affect torque. The flux density penetrating the left side of the tooth is higher than the flux density penetrating the right side of the tooth and therefore the force pulling to the left is higher than the force pulling to the right. **The net effect is that the tooth is pulled left *toward the region of higher flux density*.** This is the same direction as we would have predicted by the right-hand rule for force on conductors if the conductor had been located in the airgap flux, but the force is acting on the iron rather than the conductor.

Figure 7 - Flux Density around core tooth

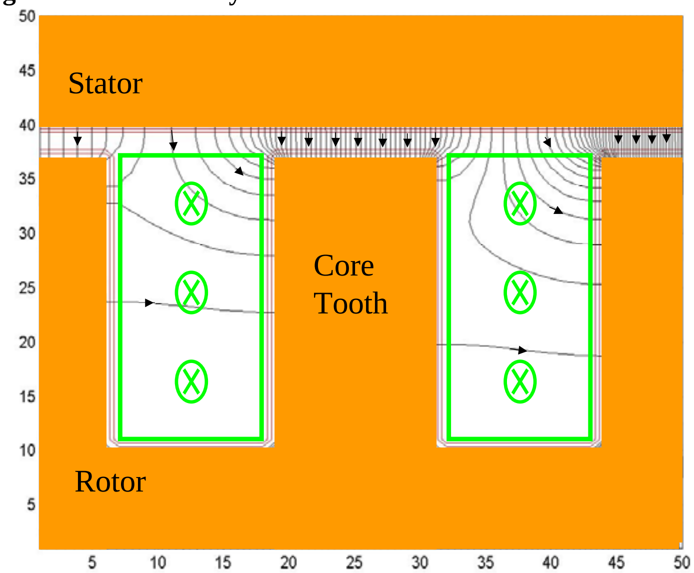
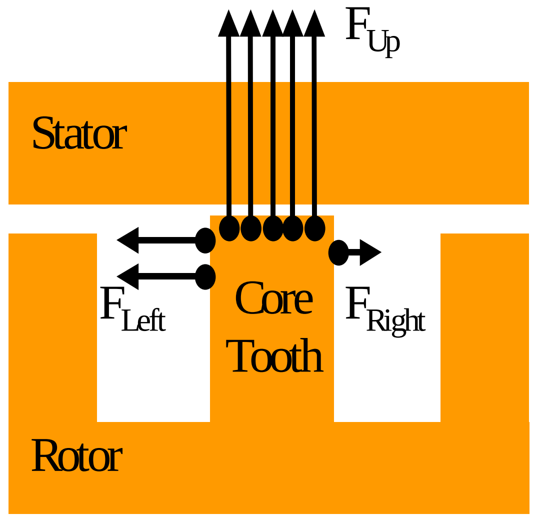


Figure 8 - Forces on core tooth



Why do some of the textbooks state that the torque-producing force acts entirely on the conductor?

For simplicity. Explaining torque production on the iron core is difficult. There is no simple equation for force on the iron like there is for force on the conductor (F = L I x B). Many authors simplify the task of explaining motor operation by "pretending" that the force acts on the conductor. In addition to simplifying the explanation, this approach of pretending the force acts on the conductor can even give the correct answer for total motor torque, IF we simply substitute airgap flux density (Bgap) into the force-on-conductor equation (changes equation #1 into equation #2). Some authors make this substitution without ever explaining why they are using flux density at one location (the airgap) to calculate force at another location (the slot). But using a force-on-conductor equation with a different flux density B than exists at the conductors does not represent the actual force on the conductors.

Although the choice to simplify the explanation may be a deliberate one for some authors, it is clear that other authors have read the simplified explanation somewhere and passed it on to others without even understanding that it does not reflect reality.

How do we know which references to believe?

There are references that explain motor operation in terms of torque-producing force on the conductor, and there are other references that identify the torque-producing force acts primarily on the core. How do we know which to believe? I suggest the following criterion:

> Criterion for a trustworthy reference: If the reference addresses both possibilities (force on core or force on conductor) and provides a theoretical, experimental, or calculational basis for determining the relative magnitudes of the torque-producing forces on the conductor and the core, then we can consider it to be a solid reference.

In "The Long Version", subsection 17.2, I identified six references that meet the above criterion. All six of these references addressed machines with conductors in slots, all six of these references provided a basis for comparing the force on core and conductor, and all six of these reference concluded that the majority of the torque-producing force acts directly on the iron core. Furthermore, these six references provide diverse proof ranging from theoretical analysis to finite element analysis simulation, to laboratory measurements.

In contrast, the references which state that the torque-producing force acts on the conductor don't even **mention** the possibility that the torque-producing force acts on the core, much less provide any basis for comparing torque on conductor vs. core![8] None of these references present a valid force on conductor equation (using Bslot) to calculate total motor torque, but some present an equation for torque using Bgap (which cannot be a valid force on conductor equation). The inescapable conclusion is that these references are providing a simplification for the sake of understandability as discussed above.

Can you show me the force on the core?

Seeing is believing. I have done a laboratory demonstration of the principles which lead to the force on the core. You can see the setup and the videotaped results for yourself here:
http://home.comcast.net/~electricpete1/torque_web/videopage.htm
http://electricpete1.tripod.com/torque_web/videopage.htm

Doesn't the cross-slot flux of Figure 4 create a force on the conductor?

Yes. We observe that the direction of flux within the slot in Figure 4 is primarily in the tangential direction. By the right-hand rule, this results in a force which is primarily radial in the downward direction (deeper into the slot). Note that this is **not** the direction associated with torque production. Even when the direction of current reverses, the direction of this force will remain primarily in the downward direction. These conclusions about downward radial force do not apply to those stator slots that contain coils from two different phases.

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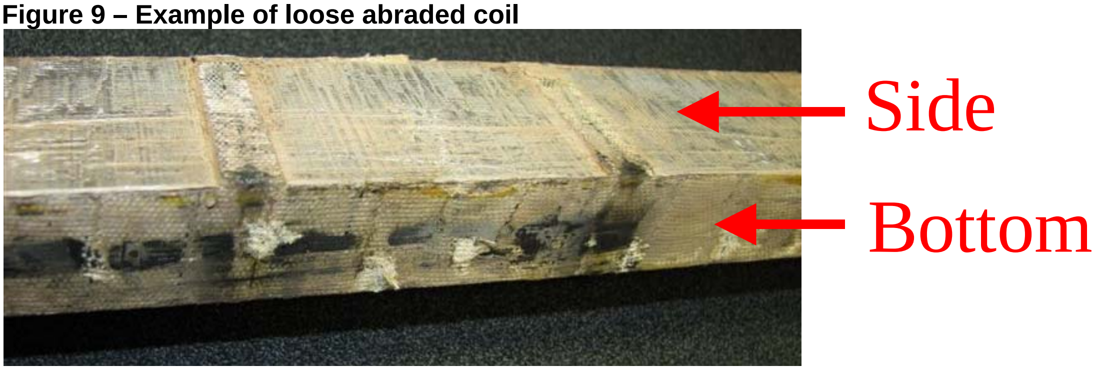
[8] Actually, I have seen **one** reference that addresses both the possibility of torque-producing force on iron or conductor and yet still concludes that the force acts primarily on the conductor. But the errors in logic of that author are readily apparent. That author supports his torque on conductor theory using only descriptions of simple devices whose conductors are not located in iron slots and he discounts the force on core on the basis of his assertion that that magnetic force cannot act in the torque-producing direction on a laminated iron core (an assertion which is easily disproved by simple experiment with permanent magnet and laminated core)

I have never heard of radial/downward force on the conductor.... Can you show me ?

Figure 9 shows a form-wound individual-coil vacuum pressure impregnated stator coil removed from a medium voltage motor. The coil sides show distinct lines indicating radial movement of the coil against the core. The pattern of those lines is interrupted at each vent duct opening, where no wear occurs and we can still easily see the original weave of the armor tape. Some people call this pattern on the side a "ladder pattern" for obvious reasons. It shows that the coil was loose within the slot and that the loose coil was acted upon by the expected time-varying radial force during operation.

Figure 9 – Example of loose abraded coil



The conclusions that can be drawn from post-mortem examination of this type of coil involve some degree of judgment and subjectivity. I don't make any claim that we can completely determine all of the forces by examining the coil. But to give ourselves the best chance to reach the correct conclusion when examining coils, we need to start with the best understanding of the expected forces within the motor. This is not served by the myth that the entire motor torque acts directly upon the conductor.

About the author

Peter has a BSEE from the University of Rochester (1987), a Master of Engineering Administration in Industrial/Systems Engineering from Virginia Polytechnic Institute and State University (1993), an MSEE from Georgia Institute of Technology (2000), and a Professional Engineer's license granted from the state of Texas by examination. He has over 20 years of experience in the area of power plant electrical systems and equipment. He has been the electric motor engineer at the South Texas Project nuclear plant since 2000.

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