Design and Performance Evaluation of a Fuzzy-Logic-Based Variable-Speed Wind Generation System

Marcelo Godoy Simões, Member, IEEE, Bimal K. Bose, Life Fellow, IEEE, and Ronald J. Spiegel, Member, IEEE

Abstract—Artificial intelligence techniques, such as fuzzy logic, neural network, and genetic algorithm, are recently showing a lot of promise in the application of power electronic systems. The paper describes the control strategy development, design, and experimental performance evaluation of a fuzzy-logic-based variable-speed wind generation system that uses a cage-type induction generator and double-sided pulsewidth-modulated (PWM) converters. The system can feed a utility grid maintaining unity power factor at all conditions or can supply an autonomous load. The fuzzy-logic-based control of the system helps to optimize efficiency and enhance performance. A complete 3.5-kW generation system has been developed, designed, and thoroughly evaluated by laboratory tests, in order to validate the predicted performance improvements. The system gives excellent performance and can easily be translated to a larger size in the field.

Index Terms—Fuzzy logic, intelligent control, power electronics, wind generation.

I. INTRODUCTION

WIND electrical power systems are recently getting a lot of attention, because they are cost competitive, environmentally clean and safe renewable power sources, compared to fossil fuel and nuclear power generation. Traditionally, wind generation systems used variable-pitch constant-speed wind turbines (horizontal or vertical axis) that were coupled to cage-type induction generators or wound-field synchronous generators and fed power directly to utility grids. Recently, variable-speed wind turbine (VSWT) systems that process power through power electronic converters have found more acceptance. Although power electronics is expensive, the larger energy capture of VSWT systems makes the lifecycle cost lower. Various voltage-fed or current-fed converter topologies have been proposed, matching with different types of machines, such as cage-type induction machines, wound-rotor induction machines, and wound-field synchronous machines. Stringent harmonic regulation on utility systems now demands that the current waveform should be nearly sinusoidal and preferably at a unity power factor.

This paper describes a variable-speed wind generation system with a squirrel-cage induction generator and double-sided PWM converters, where fuzzy-logic-based intelligent control has been used extensively to optimize efficiency and enhance performance. An extensive simulation study in the beginning validated all the control algorithms. Finally, a 3.5-kW laboratory drive system was designed and tested extensively to evaluate performance.

II. POWER CIRCUIT AND CONTROL STRATEGY

Fig. 1 shows the block diagram of the power circuit and control strategy. The turbine (vertical type) is coupled to the induction generator through a speedup gear ratio. The variable-frequency variable-voltage power generated by the machine is rectified to dc by an insulated-gate-bipolar-transistor (IGBT) PWM bridge rectifier that also supplies lagging excitation current to the machine. The dc-link power is inverted to 60-Hz 220-V ac through an IGBT PWM inverter and fed to a utility grid at a unity power factor, as indicated. The line power factor can also be programmed to be leading or lagging for static volt-ampere-reactive (VAR) compensation, if desired. The generator speed is controlled by indirect vector control with torque control and synchronous current control in the inner loops. The machine flux is controlled in an open loop by control of the \( i_{db} \) current but, in normal conditions, the rotor flux is set to the rated value for fast transient response. The line-side converter is also vector controlled, using direct vector control and synchronous current control in the inner loops. The output power \( P_o \) is controlled to control the dc-link voltage \( V_d \). Since an increase of \( P_o \) causes a decrease of \( V_d \), the voltage loop error polarity has been inverted. The tight regulation of \( V_d \) within a small tolerance band requires feedforward power injection in the power loop, as indicated. The insertion of filter inductance \( L_s \) creates some coupling effect, which is eliminated by a decoupler in the synchronous current control loops [4] (not shown). The system uses three fuzzy controllers (FLC-1, FLC-2, and FLC-3), which will be explained later. The power can be controlled to flow easily in either direction. A vertical wind turbine requires startup motoring torque. As the speed develops, the machine goes...
III. FUZZY LOGIC CONTROL

A. Fuzzy Programming of Generator Speed

Neglecting losses in the system, the line power (i.e., turbine power) with generator speed at a different wind velocity can be given by the curves in Fig. 2. The figure also indicates the operation of fuzzy controllers FLC-1 and FLC-2. If, for example, the wind velocity is $V_{at1}$, the output power will be at point $A$ for generator speed $\omega_{r1}$. The output power can be raised to the maximum value at $B$ by increasing the speed to $\omega_{r2}$. If the wind velocity now increases to $V_{at2}$, the power output jumps to point $D$. However, at this wind velocity, maximum power can be obtained by increasing the generator speed further to $\omega_{r4}$. This means that, as the wind velocity changes, the generator speed has to track it in order to extract maximum power (i.e., maximize the turbine aerodynamic efficiency). This control function is performed by fuzzy controller FLC-1, based on real-time search. Since the wind velocity is unknown, FLC-1 changes the generator speed incrementally and observes the power $P_o$. By search operation, it settles down to the optimum generator speed condition. Fig. 3 shows the block diagram of fuzzy controller FLC-1. With incrementation (or decrementation) of speed, the corresponding incrementation (or decrementation) of output power $P_o$ is estimated. If $\Delta P_o$ is positive with the last positive $\Delta \omega_r$, the search is continued in the same direction. If, on the other hand, $+\Delta \omega_r$ causes $-\Delta P_o$, the direction of search is reversed. The speed oscillates with small increment when it reaches the optimum condition. The variables $\Delta P_o$ (variation of power), $\Delta \omega_r$ (variation of speed) and $L \Delta \omega_r$ (last variation of speed) are described by triangular membership functions,
shown in Fig. 4, and the control laws are given by the rule matrix in Table I. A typical rule reads as follows:

**IF** $\Delta P_o$ is PM (positive medium) AND $L\Delta \omega^*_p$ is $P$ (positive), **THEN** $\Delta \omega^*_p$ is NM (negative medium).

The membership functions for $\Delta P_o$ and $\Delta \omega^*_p$ are asymmetrical, giving more sensitivity as the variables approach zero value. Note that, at any instant, more than one (at the most four) rule will be valid. In the implementation of fuzzy control, the input variables are fuzzified, the valid control rules are evaluated and combined, and, finally, the output is defuzzified to convert to the crispy value. The fuzzy controller output $\Delta \omega^*_p$ signal values are accumulated to generate the actual speed command signal. The output $\Delta \omega^*_p$ is added to some amount of the $L\Delta \omega^*_p$ signal, in order to avoid local minima due to wind vortex and torque ripple. The controller operates on a per-unit basis so that the response is insensitive to system variables, and the algorithm is universal to any system. The scale factors KPO and KWR, shown in Fig. 3, are a function of generator speed, so that the control becomes somewhat insensitive to
Fig. 5. Membership functions of speed for scale factor computation of FLC-1.

TABLE II
RULE MATRIX FOR SCALING GAINS OF FLC-1

<table>
<thead>
<tr>
<th>Speed</th>
<th>KPO</th>
<th>KWR</th>
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<tbody>
<tr>
<td>PSS</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>PSB</td>
<td>210</td>
<td>40</td>
</tr>
<tr>
<td>PMS</td>
<td>300</td>
<td>40</td>
</tr>
<tr>
<td>PMB</td>
<td>375</td>
<td>50</td>
</tr>
<tr>
<td>PBS</td>
<td>470</td>
<td>50</td>
</tr>
<tr>
<td>PBB</td>
<td>540</td>
<td>60</td>
</tr>
</tbody>
</table>

speed variation. The scale factors are normally generated by mathematical function, but, here, they are generated by fuzzy computation. Fig. 5 and Table II give, respectively, the membership functions and the rule matrix. The whole fuzzy controller is designed from an heuristic knowledge of the system. Of course, it is extensively iterated by system simulation study and then fine tuned by experimentation.

The advantages of fuzzy control in this case are obvious. It provides adaptively decreasing step size in the search that leads to fast convergence. Besides, the controller will accept noisy and inaccurate signals. Note that it does not need wind velocity information, and system parameter variation does not affect the search.

B. Fuzzy Programming of Generator Flux

The turbine–generator can be looked upon as the inverse of a motor–blower system where generated power is given by the cubic relation of speed \( P_o = K_e \omega_o^3 \). Therefore, the generator is running at light load most of the time with variable wind speed. At light load, the rotor flux can be reduced from the rated value to decrease the excessive core loss and, thereby, improving the efficiency of the machine-converter system. Efficiency can be optimized on the basis of an on-line search of rotor flux [5] and is implemented here by fuzzy controller FLC-2, which is described in [6]. At a certain steady-state wind velocity \( V_w \) and at the corresponding optimum speed \( \omega_o^* \) established by controller FLC-1 (see Fig. 2), the rated rotor flux is reduced by decreasing the excitation current \( i_{ds} \). This increases the torque component of current \( i_{tp} \) by the speed loop for the same developed torque. As the flux is decreased, the machine iron loss decreases with the attendant increase of copper loss. However, the total converter-machine system loss decreases, resulting in an increase of total generated power \( P_o \). The search is continued until the system settles down at the maximum power point. Any attempt to search beyond will force the controller to return to the maximum power point. It can be shown that efficiency improvement by as much as 10%–15% is possible by fuzzy controller FLC-2. The principle of FLC-2 is somewhat similar to that of FLC-1, and it starts when FLC-1 has completed its search at the rated flux condition (Fig. 2). Fig. 6 explains the operating principle of FLC-2. The membership functions of the input and output variables and the rule table are not shown. The system output power \( P_o(k) \) is sampled and compared with the previous value to determine the increment \( \Delta P_o \). In addition, the last excitation current decrement \( L \Delta i_{ds}^* \) is reviewed. On these bases, the decrement step of \( i_{ds} \) is generated through fuzzy inference and defuzzification, as indicated. As before, FLC-2 handles the signals on a per-unit basis, and scale factors KP and KIDS are given by

\[
KP = a_6 \omega + b
\]

\[
KIDS = c_1 \omega - c_2 T_e + c_3
\]

where \( a, b, c_1, c_2, \) and \( c_3 \) are constants and \( T_e \) is the estimated torque. The FLC-2 control will induce pulsating torque [6] in the generator shaft, but it will be highly attenuated by the torque control loop and the fuzzy controller FLC-3, which will be explained later. If the wind velocity changes during or at the end of FLC-2, FLC-2 control is abandoned, the rated flux is established, and the control returns to FLC-1 in steady state.

C. Fuzzy Control of Generator Speed Loop

As indicated in Fig. 1, the generator speed control loop uses fuzzy controller FLC-3 to get robust performance against turbine steady-state oscillatory torque, the effect of wind vortex, and the pulsating torque induced by FLC-2. There is also the possibility of mechanical resonance of the turbine–generator system in the absence of robust control. All the disturbance
torque components are essentially modulated inversely, so that their effect on the system is minimal. With fuzzy control, the speed control loop also gives deadbeat response [6] when the speed command is changed. The block diagram of FLC-3 is shown in Fig. 7, and the corresponding rule matrix is given in Table III. The membership functions of the fuzzy variables are not shown. Fuzzy control of the generator speed loop is essentially a proportional-integral (PI) control, where the gain factors are nonlinear and are adaptively controlled to get robust response. The speed loop error \( \Delta \omega_p \) and the error change \( \Delta \Delta \omega_p \) signals are converted to per-unit signals by the constant scale factors \( K_T \) and \( K_{CE} \), respectively, and then processed through fuzzy control to generate the torque command signal \( T_e^* \). A typical control rule can be read as follows:

\[
\text{IF } \text{error } \Delta \omega_p \text{ is PS (positive small)} \text{ AND change in error } \Delta \Delta \omega_p \text{ is PM (positive medium), THEN the torque increment } \Delta T_e^* \text{ is PL (positive large).}
\]

The membership functions of the fuzzy variables and the rule matrix were extensively iterated by simulation study until the performance was best.

### IV. COORDINATION OF SYSTEM CONTROL

The system has complex startup, control sequencing, and shutdown operations, as indicated by the simplified diagram of the Fig. 8. As wind velocity develops beyond a threshold value, the system goes through the following startup procedure.

- Close the line circuit breaker (not shown). The dc-link capacitor charges through the diode rectifier that is integral with the line-side converter and a series resistor (not shown) which is bypassed when the capacitor is fully charged.
- Start the machine-side converter and build the rated flux in the machine.

#### TABLE III

<table>
<thead>
<tr>
<th>Rule Matrix for FLC-3</th>
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<tbody>
<tr>
<td>( \Delta \omega_p )</td>
</tr>
<tr>
<td>( \Delta \Delta \omega_p )</td>
</tr>
<tr>
<td>PS</td>
</tr>
<tr>
<td>NM</td>
</tr>
<tr>
<td>PL</td>
</tr>
<tr>
<td>PVL</td>
</tr>
</tbody>
</table>

- Start the turbine–generator in the speed control mode with fuzzy controller FLC-3. As the generated power flows in the dc link, its voltage begins to rise. Fuzzy controller FLC-3, from now on, operates all the time until the system is shut down (not indicated in Fig. 8).
- As the dc-link voltage \( V_d \) reaches beyond the threshold value, the line-side converter is enabled and the dc voltage control loop is activated.

After startup, as the system tends to attain steady-state condition \( |\Delta P_o| < \varepsilon \), fuzzy controller FLC-1 is activated. The generator speed gradually builds up until maximum power is generated for the given wind velocity. If the wind velocity changes slowly, the generator speed tracks it, due to the FLC-1 control. When the FLC-1 control reaches the steady state, as indicated by a small oscillation of \( \omega_p \) about the optimum \( P_o \) point (see Fig. 2), the control is transitioned to the FLC-2 mode. At steady state of FLC-2, current \( i_d \) oscillates about the maximum power point. If wind velocity changes in either control mode, as indicated by a large increment (or decrement) of power \( \Delta P_o \), or there is a corresponding increment (or decrement) of torque \( \Delta T_e^* \), the control transfers to the nonfuzzy operation mode with the rated machine flux, as indicated in the figure. When steady-state wind velocity is reached in nonfuzzy mode \( |\Delta P_o| < \varepsilon_1 \), the control is sequenced through FLC-1 and FLC-2 modes, respectively. If
a fault develops during any operation, or the generation system is to be stopped, the shutdown mode is activated. Note that, if the line-side converter is tripped, a dynamic brake (chopper with load resistor) is switched into the dc link to limit dc voltage within a safe range.

V. HARDWARE AND SOFTWARE

As mentioned before, a complete 3.5-kW laboratory breadboard wind generation system was designed to validate all the control laws before building the 200-kW field prototype. For field application, the converter-machine system is to be scaled up, but the control hardware and software remain the same. The control hardware and software for the project are quite complex, and a detailed description is beyond the scope of this paper. Basically, the control hardware is based on two Texas Instruments TMS320C30-type digital signal processor (DSP) boards which are placed in personal computer (PC) slots with the input/output (I/O) hardware. The 32-b floating-point DSP has a 60-ns instruction cycle time, and the advantage of floating point computation is that no scaling is needed. The multitasking software, principally based on C language, is strategically distributed between the two DSP’s. The system control parameters are transported between the two DSP’s using the two independently working serial ports. The system uses a PWM chip [3] that is basically a hybrid ASIC that incorporates dedicated digital hardware and a RISC microprocessor. It receives voltage commands from the synchronous current control loops, then vector rotates such voltages into a stationary (a-b-c) frame with the help of vector angle information, converts the signals into a three-phase (a-b-c) frame, and, finally, sinusoidally modulated PWM signals are generated for gating the bridge converter. The lockout time, minimum and maximum device switching times, and current polarity signals for elimination of waveform distortion can be programmed into the chip. Since a wind turbine was not available in the laboratory, it was simulated in real time in the DSP by solving the following turbine model equations [1]:

\[ T_M = C_p(\lambda) \cdot \left[ 0.5 \frac{\rho R^2 \omega^2}{\eta_G} \right] \cdot V_w^2 \]  

(3)

\[ T_{OSC} = T_M \cdot [A \cos(\omega_{\text{turb}}) + B \cos(2\omega_{\text{turb}}) + C \cos(4\omega_{\text{turb}})] \]  

(4)

By giving command of wind velocity \( V_w \) (a software variable), and knowing the generator speed \( \omega_{\text{turb}} \), the equations are solved to generate the turbine torque \( T_M = T_M + T_{OSC} \). This signal is fed to a 7.5-hp four-quadrant laboratory dynamometer through a D/A converter. The dynamometer generates this programmable torque on the shaft of the generator under test.

VI. EXPERIMENTAL STUDY

A complete laboratory breadboard system was designed and built to experimentally evaluate the wind generation system. Prior to experimental study, the system was iterated and evaluated by extensive simulation to validate all the control strategies which are not discussed in this paper. Table IV summarizes the ratings and parameters of the experimental system. The converters were built using POWEREX IGBT...
intelligent power modules, type PM50RSA060. Basically, it is a six-pack plus brake hybrid module incorporating gate drive and protection circuitry and is rated at 600 V 50 A (inverter peak current). The induction machine was an ordinary NEMA Class B type with a 220-V 3.5-hp rating. The dc-link voltage was designed to be 300 V, considering the voltage rating constraint of the IGBT’s. Since the line-side converter has to always run in the PWM (step-down) mode, the ac line voltage was appropriately reduced by a transformer (not shown in Fig. 1). A 7.5-hp four-quadrant laboratory dynamometer was used to emulate the wind turbine (programmable shaft torque), as mentioned before.

Fig. 9 shows the static characteristics of the wind turbine at different wind velocities, where the turbine oscillatory torque components were intentionally suppressed. Basically, these are families of curves for turbine output power, turbine torque, and line-side output power as a function of wind velocity and sets of generator speed. For example, if the generator speed remains constant and the wind velocity increases, turbine power, turbine torque, and line power will increase and then will tend to saturate. The slope of increase is higher with higher generator speed. For a fixed wind velocity, as the generator speed increases, the torque and power outputs first increase and then decrease. These characteristics should also be evident from Fig. 2. The fuzzy controllers were fine tuned during experimentation. Fig. 10 shows the effect of fuzzy controller FLC-1 when the wind velocity slowly increases from 6.125 to 8.75 m/s. The generator speed tracks the wind velocity, gradually increasing the line-side power as shown. As the wind velocity settles down to the steady-state value, the generator speed step size decreases until, at the optimum power output point, it oscillates with a small step, as explained before. Note that, for a fast transient in wind velocity, controller FLC-1 remains inoperative. The dc-link voltage is analogous to the level of a low-capacity water tank with input and output water flow pipes, and maintaining its value rigidly constant is extremely difficult. A feedforward power compensator, shown in Fig. 1, helps reduce the fluctuation. However, as long as the voltage level remains within a tolerance band, the converter system will be safe and performance will be satisfactory. The dynamic brake will tend to absorb destructive voltage surges in the dc link, as mentioned before. Fuzzy controller FLC-2 starts when the operation of FLC-1 ends. Fig. 11 shows the performance of FLC-2 at a constant wind velocity of 5.0 m/s and constant generator speed of 520 r/min. The generator excitation current gradually decreases from the initial rated value that increases line-side power because of improved machine efficiency. The step size of the excitation current gradually decreases as steady state is approached, and then it oscillates about the steady-state point. The increment of power is not that large, because the machine is operating at light-load condition. In order to test the robustness of fuzzy speed controller FLC-3, the oscillatory torque components were added to the dynamometer wind turbine model. Fig. 12 shows the smooth speed profile (top) at 900 r/min with oscillatory torque (bottom) that swings from 4.35 to 5.65 N·m with an average value of 5 N·m. The additional pulsating torque introduced by FLC-2 is also highly attenuated by the FLC-3.
controller. Next, the turbine–generator system was operated at constant speed (940 r/min) and wind velocity was varied. At each operating point, the FLC-1 and FLC-2 controllers were operated in sequence, and the corresponding boost of power was observed. From these data, the respective efficiency improvement was calculated and plotted in Fig. 13. The figure indicates that the efficiency gain is significant with FLC-1 control compared to that of FLC-2. The gain due to FLC-1 falls to zero near 0.7-pu wind velocity, where generator speed is optimum for that wind velocity, and then rises. The gain due to FLC-2 decreases as wind velocity increases because of higher generator loading. During all the operation modes, the line current was sinusoidal with a unity power factor, as shown in Fig. 14. The out-of-phase current wave indicates that the system is in the generation mode.

VII. CONCLUSION

A complete fuzzy-logic-based 3.5-kW variable-speed wind generation system has been designed, and performance was
The performance of the system was found to be excellent. The control algorithms are universal, give fast convergence, and are designed for a speed control system. The advantages of fuzzy control are that a second controller programs the machine flux at light load to optimize turbine aerodynamic efficiency; a dual TMS320C30 DSP's. The system uses three fuzzy controllers: one controller tracks generator speed with varying wind velocity to optimize turbine aerodynamic efficiency; a second controller programs the machine flux at light load to optimize the generator–converter system efficiency; and the third controller gives robust performance of the generator speed control system. The advantages of fuzzy control are that the control algorithms are universal, give fast convergence, are parameter insensitive, and accept noisy and inaccurate signals. The performance of the system was found to be excellent with all controls. A higher power unit for field installation can use the same controller, but the power circuit rating is to be boosted.

REFERENCES


Marcelo Godoy Simões (S’89–M’95) received the B.E. and M.S. degrees from the University of São Paulo, São Paulo, Brazil, in 1985 and 1990, respectively, and the Ph.D. degree from The University of Tennessee, Knoxville, in 1995.

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Dr. Simões is a Registered Professional Engineer in the State of São Paulo, Brazil.

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Early in his career, he was a Faculty Member with Bengal Engineering College, Calcutta University, for 11 years, where, for his research contributions, he was awarded the Premchand Roychand Scholarship and Mout Gold Medal in 1968 and 1970, respectively. In 1971, he joined Rensselaer Polytecnic Institute, Troy, NY, as an Associate Professor of Electrical Engineering and organized the power electronics program. In 1976, he joined General Electric Corporate Research and Development, Schenectady, NY, as a Research Engineer, working for 11 years. He has worked as a Consultant in various industries, including the General Electric Research and Development Center, Lutron Electronics, Bendix Corporation, PCI Ozone Corporation, EPRI, Research Triangle Institute, Honeywell, Reliance Electric Co., Delco Remy, and Motion Control Engineering. He currently holds the Condor Chair of Excellence in Power Electronics at the University of Tennessee, Knoxville, where he has been responsible for organizing the power electronics teaching and research program for the last ten years. He is also the Distinguished Scientist of EPRI-Power Electronics Applications Center, Knoxville, TN, and an Honorary Professor of Shanghai University, Shanghai, China, and China University of Mining and Technology. His research interests spread over the whole spectrum of power electronics and specifically include power converters, ac drives, microcomputer control, EV drives, and expert system, fuzzy logic and neural network applications. He has published more than 130 papers, and holds 18 U.S. patents, with 2 more pending. He is the author of the book Power Electronics and AC Drives (Englewood Cliffs, NJ: Prentice-Hall, 1986), which has been translated into Japanese, Chinese, and Korean. He is also the Editor of the following books (Piscataway, NJ: IEEE Press): Adjustable Speed AC Drive Systems (1981), Microcomputer Control of Power Electronics and Drives (1987), Modern Power Electronics (1992), and Power Electronics and Variable Frequency Drives (1997). He was the Guest Editor of the PROCEEDINGS OF THE IEEE Special Issue on Power Electronics and Motion Control (August 1994). He has received the GE Publication Award, GE Silver Patent Medal, and a number of IEEE prize paper awards.
Dr. Bose has served the IEEE in various capacities that include Chairman of the Industry Applications Society (IAS) Industrial Power Converter Committee, member of the IAS Neural Network Council, Chairman of the Industrial Electronics Society (IES) Power Electronics Council, Associate Editor of the Transactions on Industrial Electronics, Distinguished Lecturer of the IAS and IES, and various professional committees. He is a Member of the Editorial Board of the Proceedings of the IEEE. He has also served on the National Power Electronics Committee, the International Council for Power Electronics Cooperation, and a large number of national and international conference committees. He was awarded the IEEE Industry Applications Society Outstanding Achievement Award for “outstanding contributions in the application of electricity to industry” in 1993, the IEEE Industrial Electronics Society Eugene Mittelmann Award in “recognition of outstanding contributions to research and development in the field of power electronics and a lifetime achievement in the area of motor drives” in 1994, the IEEE Region 3 Outstanding Engineer Award for “outstanding achievements in power electronics and electrical machine drives” in 1996.

Ronald J. Spiegel (M’73) received the Ph.D. degree in electrical engineering, with a minor in optical physics, from the University of Arizona, Tucson, in 1970.

His area of expertise is electromagnetics, and his Ph.D. dissertation dealt with the detection of atmospheric pollutants using laser radar (lidar) techniques. Subsequent to graduation, he was a Post-Doctoral Fellow in biomedical engineering at Duke University, Durham, NC, from 1971 to 1972, where he conducted research in the interaction of electromagnetic fields with biological media. After completing his Fellowship, he held positions in private industry, including the Boeing Aerospace Company, and at research institutes, including the IIT Research Institute and Southwest Research Institute, where he was with the Department of Defense, involved in military-related research. This research included electromagnetic compatibility (EMC), nuclear electromagnetic pulse (EMP), radar cross-section analysis, and antennas. In 1980, he joined the U.S. Environmental Protection Agency (EPA) as Chief of the Bioengineering Branch, where he supervised a multidisciplinary team of researchers with the mission of conducting research in the area of electromagnetic field interaction with biological objects relating to experimental methods, dosimetric methods, model development, and mitigation approaches. He later moved to the Air Pollution Prevention and Control Division, Research Triangle Park, NC, where he is currently researching cutting-edge environmental technology development. This area includes fuel cell application to landfill methane gas, intelligent control (fuzzy logic, neural networks, and genetic algorithms) of electric motors and turbines, and solar photovoltaics.

Dr. Spiegel is a Member of Sigma Xi and a Registered Professional Engineer. He was awarded the EPA’s Scientific and Technological Achievement Award for 1984 and 1990 and was a Finalist in the 1996 Discover Awards for Technological Innovation.