Designing Efficient Systems With the Equal Marginal Performance Principle

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Despite the number and variety of design tools available today, HVAC system designers have little guidance or effective methodologies for determining some of the most basic characteristics of their HVAC system designs. The result is that the most cost-effective configurations generally are not obtained nor are the highest potential overall HVAC system operating efficiencies achieved. To assist in improving the electrical efficiency of HVAC systems, the author has developed and successfully applied a simple but powerful general system analysis principle that can be used to help in optimizing the system design and to ensure optimal operation of nearly any modern HVAC system.

This analysis principle is called the Equal Marginal Performance Principle (EMPP) and is aimed particularly toward system configurations that use variable speed components throughout, called all-variable speed configurations. This article is intended to explain the EMPP and introduce designers to its use in optimizing system configurations and implementing optimized operating sequences.

The Equal Marginal Performance Principle

The EMPP simply states that the energy performance of any system operating with multiple modulating components is optimized when the change in system output (called the marginal system output) per unit energy input is the same for all individual components in the system.

Since system output per unit input is the definition of coefficient of performance (COP), marginal system output per unit energy input also is called marginal COP or marginal performance.

To demonstrate the EMPP as it applies to HVAC systems, consider the system and instrumentation shown in *Figure 1*. Imagine that the knobs below each com-

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ponent of the simple HVAC system shown in *Figure 1* adjust the power input to that component by changing its speed or by some other means, thereby regulating that component's output. Assume instrumentation is provided as shown to measure the total system's output (cooling capacity) and system power input (kW). How could we optimize this system at its current point of operation?

The EMPP reasons that one could do it with the following steps. First, determine the marginal contribution to total system output per unit energy input for each component. This is accomplished with the power control knob, making a very small change to the power input of each component one at a time and noting the change in system output per unit change in power input (marginal COP), afterwards each component is restored to its exact, original operating point.

Next, after the marginal COP for each component has been determined, system efficiency can be improved by reducing the power setting slightly for those components that show relatively low marginal COP and increasing the power setting slightly for those components that show the largest marginal COP such that the system remains at its original output capacity.

Then, the process of testing the marginal COP for each component and resetting the system in this fashion is repeated. Each iteration of this process will reduce the input power requirements slightly and bring all the marginal COPs closer to the same value. When all components have exactly the same marginal COP, the system is at the lowest possible power input for the current output requirements. The system is optimized.

The component-by-component testing and adjustment optimizing process described previously is similar to adaptive or auto-adaptive control approaches that have been applied to optimize very limited segments of HVAC systems.

However, these methods of directly measuring power and "learning" to optimally sequence equipment[1] or to control speed relationships[2] when only several components are being considered become indeterminate when one attempts to apply them to more complex systems with a number of components as in a typical HVAC system. Furthermore, because load and operating conditions are changing continuously in HVAC systems, the effectiveness of such approaches in actual control applications is very limited.

However, the author has developed a method of system optimization that can be applied and is effective for the most complex systems. This new network-enabled control approach, when applied to a system configured using the EMPP, results in substantial energy efficiency improvements compared to conventional control methodologies. The new method of control is called demand based control[3] because it controls equipment based on optimized power relationships rather than to meet intermediate temperature or pressure setpoints, which the EMPP demonstrates are not directly relevant to system optimization.

The EMPP requires a fresh approach to system design and operation to achieve its full potential benefits. The author's work with the EMPP also has highlighted some of the limits to its application, which will be noted later. The EMPP is a theoretical approach to system optimization. However, it has demonstrated a great deal of flexibility and success in optimizing the energy efficiency of both the design and operation of HVAC systems.

The EMPP has been shown to have associative and distributive attributes. This means that components in systems can be joined in logical combinations as a group. The components within the group can be optimized using the EMPP. And, the resulting group of components then can be optimized with other components as a single virtual component. For example, it has been shown that chiller plant energy efficiency can be improved significantly by grouping the cooling tower fans, condenser pumps, chillers, and chilled water pumps together and optimizing these components together within that virtual component—the all-variable speed chiller plant.[4]

Applying the EMPP to System Design

The ability of the EMPP to direct engineers to more successfully select key equipment design criteria and configurations for HVAC systems is a powerful feature of the EMPP. In air-based space cooling systems, cooling effect is a function of airflow and air temperature.

Imagine we are developing a VAV system schematically similar to *Figure 1*. If we want to know the optimal operating criteria for each component at any given cooling load condition, we can use the EMPP. For the EMPP, the question can be posed as "At what point does the marginal overall system efficiency

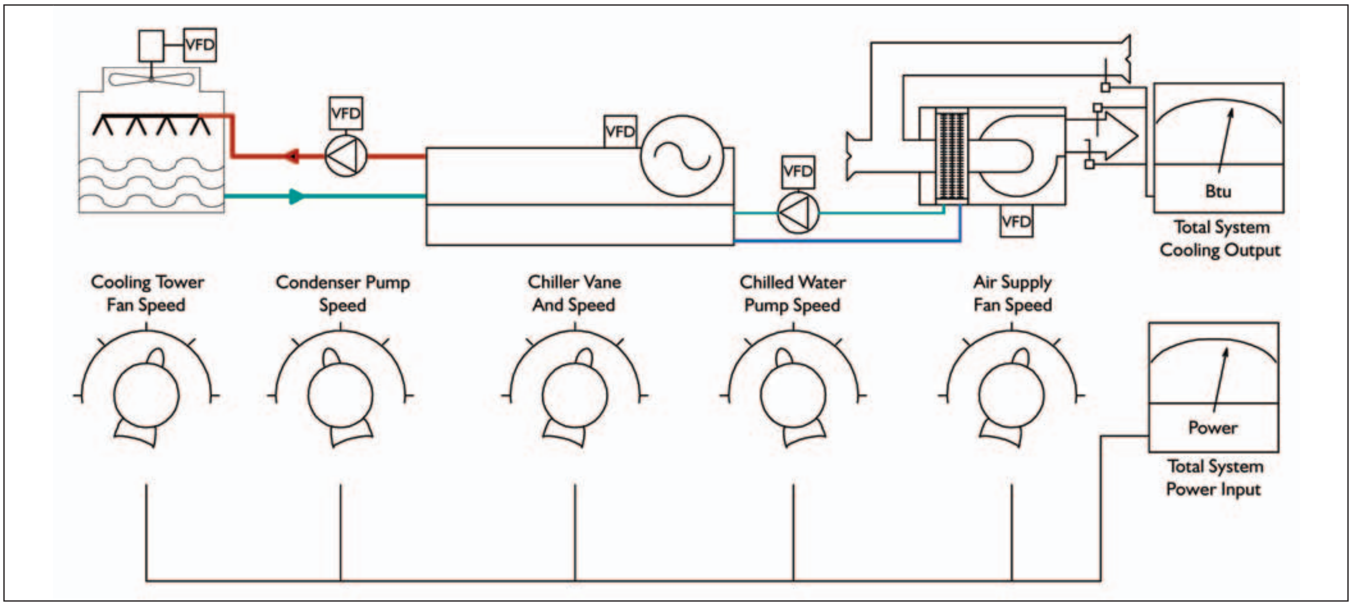


Figure 1: All-variable speed HVAC system with local efficiency monitoring and component control.

with respect to energy input for the chiller plant equal that of the cooling delivery system?"

To answer this question, the designer can use the associative feature of the EMPP and group the cooling tower, condenser pump, chiller, and chilled water pump together as a single component called the chiller plant. Then, the designer can optimize those components with each other at various operating conditions and use that group as a single virtual component to optimize the entire system with the only remaining element, which is the fan and cooling coil. The designer can determine what combination of power provided to the chiller plant and the fan result in optimized energy operation for any cooling load.

Since the EMPP states that the system will be optimized when the change in system output per unit input (marginal COP) is the same for all components, such an analysis correctly is begun by viewing a COP calculation for the system as a function of component power input. At any given point of operation, the COP of the system is easily calculated. Since COP is output divided by input, the system component COP (component COP is defined as the system output as a function of the power input for that component with all other components at constant power) is simply the system output (Q) divided by the power demand of that component.

$$\mathrm{COP_{COMPONENT}} = Q/\mathrm{COMPONENT\ POWER\ INPUT} \quad (1)$$

The total system COP is then the reciprocal of the sum of the reciprocals of each component COP. The COP of a system consisting of n components could be calculated as follows:

$$\mathrm{COP_{SYSTEM}} = 1/\left(1/\mathrm{COP_{COMPONENT\ 1}} + 1/\mathrm{COP_{COMPONENT\ 2}} + \ldots\ 1/\mathrm{COP}_{\mathrm{COMPONENT}\ n}\right) \quad (2)$$

However, determining the system marginal COP for each component can be a complex process. This is due to the need to use both system output and system input and account for the performance interdependence among the system components.

When power adjustments are made for one component while power to others remains the same, the operation and performance of the other components in the system may change. The calculation for marginal system COP of any component requires a mathematical expression that calculates the total system cooling output (Q) based on separate variables that represent the power to each component in the system.

The marginal performance (or marginal component COP) at a point of operation for any component is the partial derivative of the expression of total system output as a function of the energy input requirements with respect to that component's power input.

$$Q = f\left(\text{Component1 power, Component 2 power} \ldots \text{Component n power}\right) \quad (3)$$

$$\text{Marginal COP for component x} = \partial Q/\partial \text{ Component x power} \quad (4)$$

Creating an expression for the entire system and adequately deriving the marginal COP for each component mathematically can be time consuming. However, the process described for the following example is an approach that approximates the component marginal system COP for design optimization purposes using curve fitting techniques.

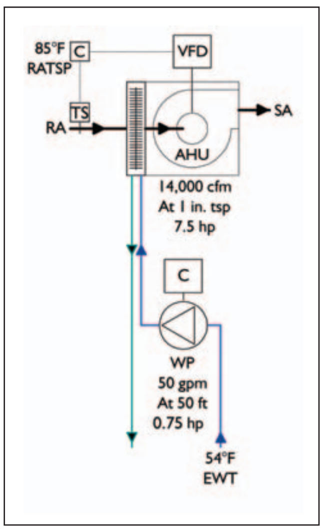
Tools are being developed that use the EMPP to make the optimized equipment selection and control sequence development a simple and straightforward process for even complex HVAC systems.

An EMPP Based Design Example

As a simple example of applying the EMPP for optimization, suppose a designer needs to develop a cooling system for a remote electronics/communication building. It is determined that the design peak load is 25 tons (88 kW). The engineer decides to use an adjacent stream to provide cooling. The stream water is the result of glacial melt. It is very clean and available at a constant 54°F (12.2°C) year-round.

Because power is produced on site and is very expensive and limited, it is decided that the fan will be variable speed and the speed will be adjusted to vary capacity as may be required.

The engineer develops a design where the pump is sized to provide cooling water with a 12°F (6.7°C) ΔT for the load. The total pump head at maximum flow is calculated at 50 ft (150 kPa), and the flow is 50 gpm (3.2 L/s). The power requirement is calculated to be 0.6 hp (0.5 kW) and a 0.75 hp (0.56 kW) pump is selected. The air handler and cooling coil are sized to provide cooling with 65°F (18.3°C) supply air temperature and 85°F (29.4°C) return air temperature at peak load conditions. Because this is located in a low humidity area, the cooling is assumed to be entirely sensible and the designer selects a 14,000 cfm (6610 L/s) air handler and a coil with a log mean temperature difference (LMTD) of approximately 15°F (8.3°C) at design conditions that will provide the required cooling. With the air filter, cooling coil and ductwork, a total static of 1 in. w.g. (250 Pa) is calculated and the maximum fan power required is determined to be 6.4 hp (4.8 kW). This initial configuration is shown in *Figure 2*.



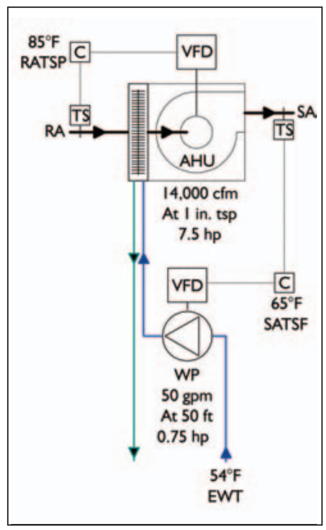


Figure 2 (left): Example system, initial configuration. Figure 3 (right): Example system, alternate initial configuration.

The initial design of the control system incorporates control of the fan speed (flow) to maintain a continuous 85°F (29.4°C) return air temperature. The pump runs continuously with the fan. It is suggested that energy may be saved by varying the speed of the pump and maintaining a constant supply air temperature or even resetting the supply air temperature in accordance with some optimization algorithm. This alternate initial configuration is shown in *Figure 3*.

The designer decides to use the EMPP to determine if an opportunity exists to better optimize the equipment selection or control to reduce energy use of this system. To do so, the designer decides to develop an algorithm for this simple system that relates output as a function of the power input of the two components.

Since the water is pumped from and back to the stream at the same level, both the pump and fan have only dynamic head requirements in this simple example. With only dynamic heads, the fan and pump laws permit flow for each to be expressed in terms of power as:

$$\text{Pump Flow} = (\text{Design maximum water flow}) \times \left(\%\text{Pump Power}^{(1/3)}\right)$$

$$\text{Fan Flow} = (\text{Design maximum airflow}) \times \left(\%\text{Fan Power}^{(1/3)}\right)$$

The designer knows if input power is used, the varying motor and inverter efficiencies mean these relationships do not hold over the entire speed spectrum. But, over the range upon which this analysis is focused, these relationships are determined to be sufficiently accurate.

To express total system output, the designer considers the EMPP approach for component contribution to overall capacity and develops the following formula based on the heat transfer characteristic provided by the cooling coil manufacturer (or by using general LMTD coil equations) and rules with a fixed entering air temperature and a fixed entering water temperature.

Due to the inherent simplicity of the heat transfer in this case, the engineer can combine and simplify the equation or use curve fitting techniques and retain accuracy within several percent at typical operating conditions.

Again, the design engineer understands there are limits to the accuracy of such a calculation over wide loading ranges but can construct a sufficiently accurate expression over the desired range to use to analyze this configuration. The formula for system output as a function of the two inputs developed using curve fitting techniques is:

$$Q = 244{,}647 \times (\text{FHP}^{0.125}) \times (\text{PHP}^{0.055})$$

Where Q is system output in Btu/h, FHP is fan horsepower input, PHP is pump horsepower input. Similar formula can be developed for calculating output as function of input using SI or other units.

Using the EMPP, the engineer understands that the system will be optimized when the marginal performance of the two components are equal to one another. To do this, the engineer takes the partial derivatives of the previous equation.

The partial derivative of the output with respect to fan power is:

$$\partial Q / \partial\, \text{FHP} = 0.125 \times 244{,}647 \times \text{FHP}^{-0.875} \times \text{PHP}^{0.055} = 30581 \times \text{FHP}^{-0.875} \times \text{PHP}^{0.055}$$

The partial derivative of the output with respect to pump power is:

System Capacity (Percent of Max.)	Fan			Pump		
	Power (hp)	Speed (Percent of Max.)	Marginal Performance (Btu/h per hp)	Power (hp)	Speed (Percent of Max.)	Marginal Performance (Btu/h per hp)
100%	4.00	100%	9,400	1.75	100%	9,400
90%	2.24	83%	15,080	0.99	83%	15,080
80%	1.15	66%	25,985	0.51	66%	25,985
70%	0.55	52%	47,800	0.24	52%	47,800

Table 1: Optimized fan and pump operation at various system capacity points.

$$\partial Q / \partial \text{PHP} = 0.055 \times 244{,}647 \times \text{FHP}^{0.125} \times \text{PHP}^{-0.945} = 13456 \times \text{FHP}^{0.125} \times \text{PHP}^{-0.945}$$

With an understanding of the EMPP, the engineer knows this system will be optimized when the system output is 100% *and* the two previous expressions are equal to one another. Again, the benefits of digital computation permit the engineer to reasonably quickly solve this problem with any one of several different methods. Using a spreadsheet analysis, the optimized result at design condition is calculated to be:

System Capacity (percent of original design): 100% (25 tons or 88 kW)

Fan Power (percent of original design): 62.5% (4 hp)

Pump Power (percent of original design): 292% (1.75 hp)

Marginal System Performance (Btu/h per hp): 9,400 (identical for both fan and pump)

Energy Reduction Compared to Original Design: 17%

So, the engineer finds that by applying the EMPP to this simple system, it is possible to reduce the power consumption at peak conditions of the system by 17% by increasing pumping power and decreasing fan power without making any major configuration changes (piping, ductwork or cooling coil). To implement the necessary changes, the engineer could select a new 1.75 hp pump rated at 72 gpm (4.5 L/s) and 102 ft (306 kPa) head. The fan motor size would be reduced and the fan is belted to provide 12,000 cfm at 0.75 in. (5664 L/s at 188 Pa) of total static pressure.

Designing with the EMPP is an iterative process. At this point the designer would review the pipe sizing in light of the 44% increase in water flow rate. A new cooling coil also may be selected and a new function of system output would be developed and evaluated for optimized operation. However, for this example, it is assumed that the design optimization process ends at this step with the 17% peak load operating efficiency improvement.

Applying the EMPP to Optimize System Operation

The designer now wishes to determine how the system can be optimally operated. As shown earlier, the EMPP can help optimize sizing and design criteria for full load design conditions as described earlier, but most HVAC systems typically operate only a small portion of their time at or near full load conditions. The EMPP also is usefully applied to optimize the *operation* of HVAC systems at part load conditions using demand based control, a corollary, or the EMPP.

By sizing variable speed components according to the process described above, the system is not only optimally configured for full load conditions, but is also ready to be optimized for superior part load operating efficiencies by applying the optimum operating power relationships (demand based control) determined by applying the EMPP. To do this, the EMPP is used again.

The algorithm that expresses output as a function of component input is solved at various outputs (system capacity levels) with the partial derivatives set equal at those points to determine the optimal power relationship between the fan and pump at those part load conditions. The results of this process for the simple example system are shown in *Table 1*.

Note in *Table 1* that the marginal performance for the fan and pump are identical at each capacity point. This means according to the EMPP that the system operation is optimized at these relative power settings. By calculating the speed from the optimized power settings, it is seen that the optimized operation for this simple system involves operating the pump and fan at identical speeds (percent of maximum rpm) at all load levels. Thus, optimized control for this example is simple, a single control loop that operates the fan and pump at identical speeds to maintain the 85°F (29.4°C) return air temperature setpoint. The configuration of the optimized solution is shown in *Figure 4*.

Achieving optimized control by operating system components at identical speeds is due to the simplicity of the example. However, the process described previously can be used to determine the relationship for distributing power to the various components of nearly any system that will result in optimal operation at any load condition.

As can be seen for this example, demand based control incorporates no specific supply air temperature setpoint. In many applications, supply air temperature will be required to have limits so that it remains within an acceptable range for adequate air mixing, humidity control, etc. However, using demand based control dramatically changes operating sequences since intermediate temperature and pressure setpoints are not used except as limiting functions to the simple direct optimization controls that operate the system.

When demand based control is employed, the supply air temperature varies with changes in load conditions. To accommodate changing supply air temperature, cooling effect (temperature independent) VAV box control[5] is used to maintain stable VAV box and zone temperature control. Also, the variable supply air temperature may require special attention to ensure humidity remains within limits depending on the climate, application, and specific design criteria.

For chilled water distribution circuits, demand based control operation results in the potential for large operating energy efficiency improvements. The EMPP teaches designers that input power relationships, not temperature or pressure setpoints, are the critical components of optimized control. Control of the chilled water valves need not be aimed at maintaining a specific supply air temperature setpoint but rather to maintain an optimum fan speed (power) relationship with the current chiller plant power demand. This greatly simplifies the control requirements of the cooling coil valves.

Such distribution systems can be made far more efficient than conventional distribution systems by replacing stand-alone PID control of individual valves with network-enabled resource allocation strategies.

Work to date with the EMPP shows that control valves can be selected with essentially zero pressure drops and may be controlled with intelligent iterative control schemes[6] to keep fans operating at optimal speed.

The resulting distribution pumping systems operate much more effectively with greatly reduced pump head and power requirements. Chilled water flow may be regulated to ensure all loads are satisfied according to new network methods such as the valve orifice area method[7] rather than differential pressure control techniques.

Limitations on the Use of the EMPP

The EMPP can be applied to assist designers in selecting components and developing optimum operating sequences for nearly any HVAC system that is composed of multiple modulating components in which operating efficiency is a function of capacity. The flexibility of the EMPP means that individual elements can be grouped together in a variety of combinations and each group of combined elements can be optimized together. However, some limitations exist to the use of the EMPP that designers should keep in mind. Among the most important limitations are:

1. The EMPP analysis cannot be used for overall optimization of a system that provides heating and cooling simultaneously. This limitation applies to systems with terminal reheat (when the reheat is active) or a system that in any other way has an indeterminant output. Such optimization is beyond the scope of the EMPP. However, elements of such systems can be optimized with regard to certain criteria and operation with the EMPP after the ideal combination of heating and cooling or other multiple output choices has been determined. In many cases, the EMPP also can be used in separate analyses to help determine the ideal combination of multiple output choices.

2. To use the EMPP as an optimization tool and to ensure there are not localized points of optimization that missed, the system output as a function of component energy input must for each component be continuous with positive but decreasing slopes over the ranges used. Such characteristics are typical for

systems consisting of variable speed driven components when operating within their normal recommended ranges.

3. The operating ranges in which equipment is optimized should be limited as may be required to remain within manufacturers' published temperature, pressure, flow and rates of change limitations.

4. Designers need to be aware that component input energy must be all-inclusive and system output must be useful output. For example, when supply air temperature is reduced, additional dehumidification of outside air likely will be provided by the cooling coil. This extra energy requirement must be part of the system energy input requirement and the output function may have to be limited to only useful cooling to the space. Conversely, as the supply air temperature is raised, inadequate dehumidification of supply air at the higher temperature conditions may mandate a higher energy input to provide additional latent cooling along with the sensible cooling to achieve a useful output to maintain satisfactory comfort conditions.

These limitations to the EMPP do not normally inhibit its application at typical design points and operating conditions for HVAC systems, but they need to be considered, especially when initial equipment configurations, sizing or applications may be unusual.

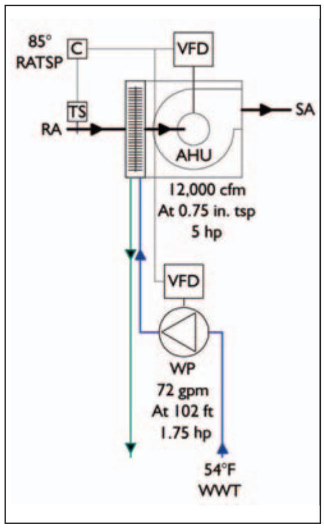


Figure 4: Example system, final optimized configuration.

Design Insights Using the EMPP

As designers become more familiar with the EMPP, they will find they can use it to improve both system configurations, and also operating sequences with its corollary, demand based control. One of the most enlightening general aspects of the EMPP is that it encourages designers to better visualize how each component contributes directly to the system's overall function.

Using the EMPP, it is easier to correctly size condenser pumps, tower fans, and other elements critical to HVAC systems that have sometimes been misconstrued as parasitic components because they have not been seen as contributing directly to system capacity.

The EMPP teaches designers that for optimum operation, these components must contribute to the system cooling output the same as fans and chillers. It becomes clear that optimizing overall system function requires that each HVAC system component be sized and optimized in its operation using identical methodologies.

Summary and Conclusions

The EMPP is not limited to HVAC applications. However, when applied to HVAC applications, it provides an important new perspective for designers on how system components can be configured and operated for more effective and efficient operation. By applying the EMPP to design and operation of HVAC systems, new methods of component selection and operation are possible. These can result in significant reductions to overall annual electric use of HVAC systems without increasing equipment cost or other capital costs. The large potential opportunities for improved efficiency by widespread application of the EMPP in design and operation of large systems, as well as packaged unitary products, makes the EMPP an evaluation and analysis approach that should be considered by engineering firms, equipment manufacturers, and contractors.

More importantly, the EMPP can be incorporated into manufacturers' research and development programs and a topic of research efforts by academic and other institutions that wish to promote improvements in electrical efficiency.

One particularly timely aspect of optimization with the EMPP is that it provides a simple but effective optimization process to better select and connect factory integrated equipment and controls component packages together. This potential application of the EMPP means that less costly prepackaged integrated controls and equipment solutions can be made as efficient as custom designed solutions.

Since the EMPP is a radically new concept for HVAC system design and operation, it is obvious that considerable education and/or reeducation of designers and operators is necessary to achieve the substantial improvements and widespread application in HVAC system performance. It is the intent of the author to work with others in the industry to make information, tools and simplified solutions for design and operation available.

To that end, comments and suggestions from readers regarding this new design and operation principle are most welcome and appreciated.

Acknowledgments

The author would like to acknowledge the editing and content suggestions from Roger Haines, Ron Anderson, Alan Wright, Ph.D., John House, Ph.D., and William P. Bahnfleth, Ph.D., for help in improving the clarity of this material. The interest and assistance of these and other individuals who have supported the author's development and early applications of this new system design and operating principle is greatly appreciated.

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