Power Supply Design in a Modular LED Dance Floor

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***Abstract*—**The Washington University in St. Louis IEEE student branch are designing a next-generation LED dance floor that synthesizes color, music, and touch in a way that has not been done in any other device. The device is being designed with modularity and expandability as key features and therefore a solid, reliable power system was needed. This report focuses on the project's power distribution and regulation design including how the use of switching voltage regulators increased the power supply's efficiency from 37% to 75%, how delivering fused 120V AC power to the modules instead of low-voltage AC or DC reduced cost, complexity, and weight, and how the end result was a reliable, robust, and efficient power system that enables assembly of the dance floor in any shape and size.

I. Introduction

Power distribution is arguably the oldest aspect of electrical engineering. From Thomas Edison's pioneering Edison Electric Light Company of 1878 to the power-saving "smart grid" systems of today, distributing power reliably and efficiently has been a focus of electrical engineers for well over a century. Today people are surrounded by electric devices since childhood and power distribution may not seem like much of a challenge. However, any sensitive electrical device must have a well-designed power supply; likewise, a system of devices linked together must have an equally well-designed power distribution schema. The main goal of the dance floor project was to design a dance floor made up of many subunits that could be assembled and disassembled quickly and therefore power distribution and regulation both had to be addressed.

II. Design Overview: Investigating Linear Voltage Regulation

From the beginning it was decided that the dance floor needed to be, above all, portable. The Washington University IEEE student branch built their first dance floor in 2006. It was designed essentially as a single structure that took a lot of time to set up and take down. The ability to easily assemble and disassemble the floor along with ease of travel and operation were considered crucial in the early design phases of the new dance floor project. So, rather than designing a single dance floor structure, the floor was divided into individual two-foot-by-two-foot "modules" which would each contain 16 pixels in rows of four as shown in Fig. 1, and each pixel would have four LEDs: a red, blue, green, and white LED.

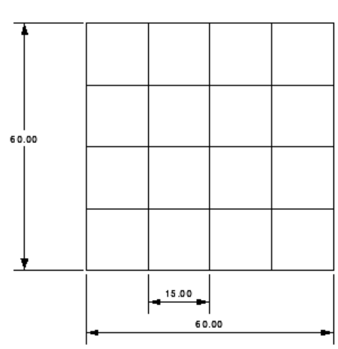

Fig. 1. Physical layout of a single module. Each module is 60 cm by 60 cm and has 16 pixels driven by four RGBW LEDs each.

The power supply design, therefore, would have to be able to drive 64 LEDs and the control circuits. The maximum voltage of any of the parts in each module was the white LEDs which had a nominal forward voltage of 6.4 V. Therefore, the target input voltage range was decided to be 9 VDC with a maximum allowed input of 12 VDC to allow ease of use with widely-available COTS power supplies to reduce cost. However, this input voltage range was well above the voltage level of the logic circuits which run at a nominal 3.3 V. To account for this, a DC voltage regulator had to be designed and placed between the input supply and the logic power bus. To accomplish this a few different options were available.

First, a series linear regulator could be used to drop the voltage down to 3.3 V. Series linear regulators have the advantage of being very inexpensive and require few external components. A common variant is the LM317 adjustable voltage regulator sold by National Semiconductor [1]. Such a device requires only two bypass capacitors and a resistor voltage divider to operate as shown on the right in Fig. 2.

However, the basic design of series regulators poses significant drawbacks. A series regulator works by acting as a dynamic resistor that changes with the load. A simple example of a series linear regulator is shown on the left in Fig. 2. In this example a transistor Q is acting as a series resistor to R2, the load. A more sophisticated design would implement negative feedback to Q’s base to change the equivalent resistance of Q as the load R2 changes, and this is essentially how all real linear regulator work [2]. In practice, this property means that the linear regulator’s steady state response can be modeled simply as a resistor voltage divider [3], as shown in the center of Fig 2. In this model, the resistor R1 represents the equivalent resistance of the regulator and R2 represents the equivalent resistance of the load.

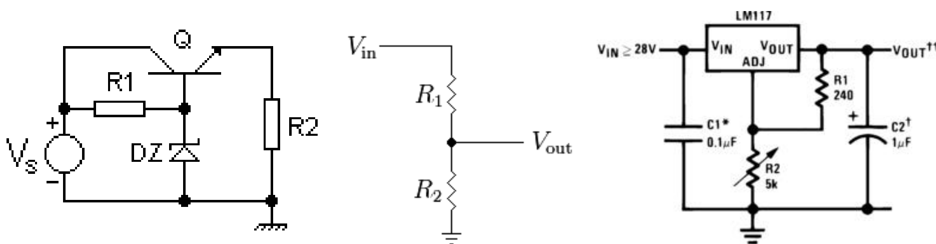

Fig. 2. On left: schematic diagram of a simple series linear regulator [2]. The regulator acts like a variable resistor making it inefficient for higher drop voltages.
In center: a resistor divider circuit [3]. This circuit accurately models the steady state behavior of the series linear regulator.
On right: typical application schematic for an LM117/LM317 linear regulator [1].

Using this model it is evident that the linear regulator is quite inefficient, particularly with higher voltage drops across R1. As the input voltage rises relative to the output voltage the power loss increases across R1. The theoretical efficiency, therefore, was calculated as shown in (1).

$$Eff = \frac{P_{\mathrm{load}}}{P_{\mathrm{reg}} + P_{\mathrm{load}}} = \frac{V_{\mathrm{out}}}{V_{\mathrm{drop}} + V_{\mathrm{out}}} = \frac{V_{\mathrm{out}}}{V_{\mathrm{supply}}} = \frac{3.3\ \mathrm{V}}{9\ \mathrm{V}} = 36.9\ \% \tag{1}$$

To investigate the impact of this low efficiency the power loss in the regulator was then calculated. First, the total current draw per module had to be calculated. This was accomplished by adding up the current draw of each device on the circuit board using the manufacturer’s datasheet for each part as shown in Table 1.

TABLE I
CURRENT DRAW PER MODULE BY DEVICE

Device		Number in Circuit	Min Load (mA)	Typical Load (mA)	Max Load (mA)
STM32F105RCT6	[4]	1	32.7	50.55	68.4
TLC5940	[5]	8	12	30	60
DS90LV049	[6]	4	20	21.2	30
74VHC21	[7]	1	0.001	0.002	0.02
TMP36	[8]	1	0.02	0.025	0.03
		Total Current Draw:	208.721	375.377	668.45

Equation (2) and (3) show how the worst-case total power draw for a 9 V power supply using a linear regulator and the power loss through the regulator was calculated.

$$P_{\mathrm{drop}} = 9\,\mathrm{V}\,(0.66845\mathrm{A}) = 6.02\,\mathrm{W} \tag{2}$$

$$P_{\mathrm{reg}} = (1 - Eff)(P_{\mathrm{drop}}) = 0.633(6.02\,\mathrm{W}) = 3.813\mathrm{W} \tag{3}$$

To reduce heat dissipation inside the modules, which are unventilated, and to reduce cost and assembly complexity another design requirement that was established was that the regulator should not produce more heat than it can dissipate without a heatsink. Therefore, using the calculated power loss, the equilibrium temperature of the regulator was calculated with (4).

$$T = T_a + \theta_{JA} P \tag{4}$$

Where T_a is the ambient temperature of the surrounding environment, θ_{JA} is the thermal resistance of the junction to air, and P is the power dissipated in the device. Using the   of a standard TO-220 integrated circuit [9] and the power dissipation calculated earlier:

$$T = 25°\mathrm{C} + 62.5(3.813\mathrm{W}) = 263.3°\mathrm{C}\; \textit{in air} \tag{5}$$

As (4) and (5) show, the theoretical worst-case open-air temperature of an LM317 in this application is 273.3 degrees Celsius. Since the absolute maximum temperature rating for the LM317 is 125 degrees Celsius the LM317 would rapidly enter thermal shut-down and the dance floor logic circuit would lose power. In light of the poor performance of the linear regulator, a different power supply design was sought.

III. DESIGN OVERVIEW: INVESTIGATING SWITCHING VOLTAGE REGULATION

A much more efficient power supply design is the step-down switching voltage regulator. Switching regulators operate on a different principle than linear regulators. Rather than reducing the supplied voltage by introducing a new load, switching regulators “switch” the power supply on and off at a specific frequency and at the right duty cycle to maintain an average voltage equal to the desired output voltage. A simple switching regulator is shown in Fig. 3 below. The switching regulator switches the power source on and off relying on passive components such as capacitors and inductors to store energy and smooth the output voltage. The result is a power supply that is often more than twice as efficient as their linear regulator counterparts [10].

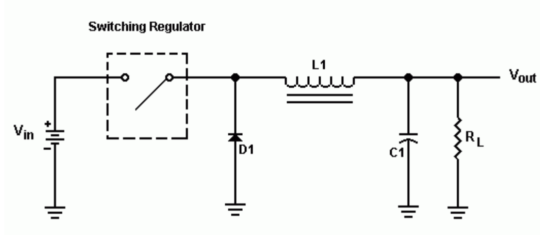

Fig. 3. Schematic diagram of a simple step-down switching regulator [10]. The regulator "switches" the power supply relying on stored energy in passive components which results in high efficiencies.

Like linear regulators, switching regulators are also sold as convenient integrated circuits. The LM2575-3.3 step-down switching regulator implements the negative feedback necessary to provide a stable 3.3V voltage output and was chosen for the dance floor project after researching different product offerings for the lowest-cost device that fit the design requirements. Comparing Fig. 3 to Fig. 4 it is evident that the LM2575 replicates the behavior of the black box in the simplified schematic with only the addition of a smoothing bypass capacitor on the input [11].

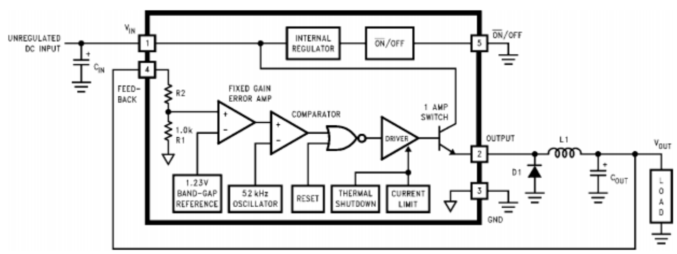

Fig. 4. Block diagram of the LM2575 step-down switching regulator as shown in the product datasheet [11]. The LM2575 implements the switching and negative feedback functions of the black box in the simplified schematic in Fig. 3.

Although the LM2575 behaves a black box in the circuit, a few considerations were made to ensure proper output behavior. Since the regulator operates on the principle of switching the supply on and off to reduce the voltage, there will always be a voltage ripple in the regulated output. To minimize this voltage ripple an inductor and a bypass capacitor are connected to the output of the regulator in a low-pass filter configuration. The values of the capacitor and inductor must be chosen to minimize the output ripple for a given nominal load. To aid in this decision the datasheet from National Semiconductor gives a recommended inductor value based on the desired load through the provided chart in Fig. 5 [11]. For this application the maximum load is 0.67 A and the maximum input voltage is 12 V; therefore a 330 μH inductor was chosen.

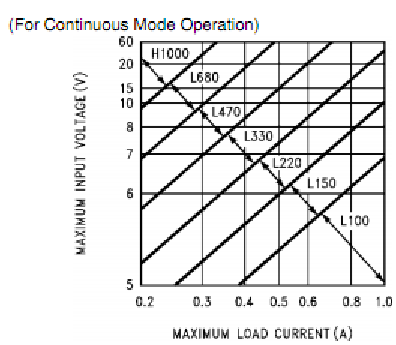

Fig. 5. Inductor values recommended by National Semiconductor in the LM2575 datasheet [11].
For the dance floor's application a 330 μH inductor was optimal.

Finally, the value of the output bypass capacitor was chosen. The capacitor was also chosen by following the manufacturer's recommendations [11]. An equation was provided to calculate minimum value for the capacitor as shown in (6).

$$C_{out} \geq 7785 \frac{V_{in\,\max}}{V_{out} \cdot L} = 7785 \frac{12\text{ V}}{(3.3\text{ V})(330\,\mu\text{H})} = 85.8\,\mu\text{F} \qquad (6)$$

According to the manufacturer the output bypass capacitor had to be at least 85.8 μF. A 330 μF capacitor was chosen in the end to ensure that the voltage ripple was sufficiently minimized for the sensitive field programmable gate array and flash memory in the logic circuit. A large bypass capacitor also minimizes the transient response of the regulator which becomes important with sudden changes in the load, for example, when the entire floor goes from the off state to full brightness. The final switching power supply schematic is shown below in Fig. 4. Once the 3.3 V voltage regulation was addressed the last remaining design issue was how to provide 9 – 12 VDC to the modules. As explained in the next section, inexpensive COTS 120 VAC to 9 VDC adapters were eventually chosen for each module over one large DC power supply for the entire floor.

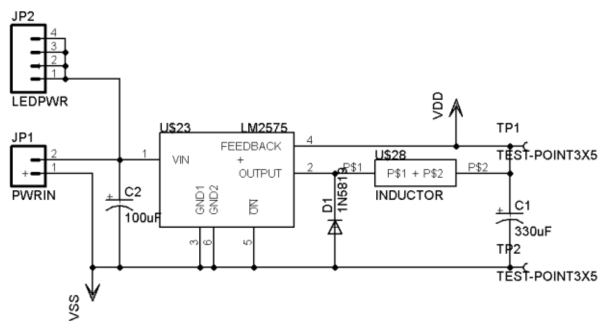

Fig. 6. The switching regulator circuit as implemented in EAGLE® with an LM2575-3.3 regulator.

The theoretical efficiency of this circuit is described by the manufacturer in the datasheet with a graph showing typical efficiency curves for different voltages and loads as shown in Fig. 7 [11]. Although a curve for 3.3 V output is not shown, it can be extrapolated by noticing that the peak efficiency will be at a lower input voltage than the peak at 5 V and will be slightly lower. Therefore, according to the chart, a nominal supply voltage of 9 V, an output voltage of 3.3 V, and typical supply current of 0.375 A will yield a typical efficiency of around 75 %, a very respectable improvement over the linear regulator.

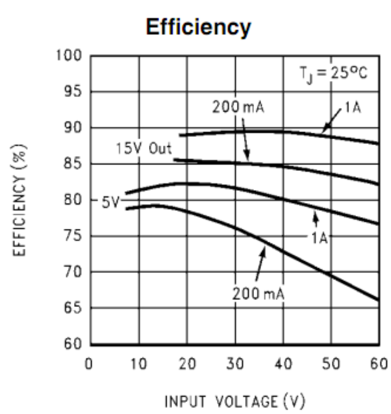

Fig. 7. Typical efficiency curves of an LM2575-3.3 regulator as provided by the manufacturer [11]. Extrapolation from the graph suggests a typical efficiency of about 75% for 3.3 V, 375 mA output and 9V input.

IV. Design Overview: Power Distribution

Once power regulation was addressed the issue of power distribution was investigated. In addition to the decision to design the dance floor modularly, another early design decision was that the modules should not have to be arranged in a specific way like a jigsaw puzzle; rather, they should be like tiles or building blocks which work any way they are arranged. For example, one module should not have to always be "the module that goes on the northeast corner of the floor". This also meant that the floor should be able to take on any shape the user would want. For example, "gaps" in the floor should be possible such that a DJ can set up his table within the edge of the floor as shown in Fig. 8.

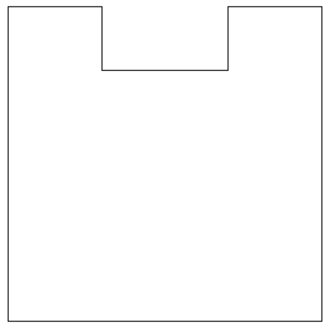

Fig. 8. A valid configuration of modules. Gaps must be allowed in the floor precluding the possibility of distributing power in a chain-like fashion.

These requirements posed a few implications. First, the modules in the floor cannot be connected in a chain, because the modules may not always be contiguous. Gaps in the floor mean that a single snaking path through the floor would not be possible. This problem was solved by having power travel through the modules not in one direction, but two: horizontally and vertically. In this configuration, each module's power supply is connected directly to the power of its four neighboring modules. In this way, any module can be removed from the floor without interrupting the supply of power to the rest of the modules.

The next part of the design that had to be considered was what kind of power would be supplied to the modules. Initially low voltage DC was considered, since the modules themselves require DC power and the highest voltage needed was 6 volts for the LEDs. This was, however, quickly abandoned when the number of modules, the power draw per module, and the resistances of the cables were taken into account. To investigate the power loss when supplying the floor with DC power a PSpice model was used that modeled each wire and module as resistive loads. Equation (7) shows how the resistance of a wire can be calculated from its physical dimensions and conductor material [12].

$$R_{eq} = \frac{pL}{A} \tag{7}$$

p is the resistivity of the wire, L is the length, and A is the cross-sectional area of the wire.

The equivalent length of wire between modules was assumed to be one meter and the wire gauge was known to be 16 AWG stranded copper. Using a look-up table 16 AWG wire was found to have a cross-sectional area of 1.31 mm^2 and copper was found to have a resistivity of 1.68×10^{-8} ohm-meters [13]. Using these parameters the theoretical resistance per wire was calculated as shown in (8) and the equivalent resistive load of each module was calculated using ohm's law as shown in (9).

$$R_{eq} = \frac{(1.68\times10^{-8}\,\Omega\cdot\mathrm{m})(1\ \mathrm{m})}{1.31\times10^{-6}\,\mathrm{m}^2} = 0.0128\,\Omega \tag{8}$$

$$R_{eq} = \frac{V}{I} = \frac{9\ \mathrm{V}}{0.670\ \mathrm{A}} = 13.4\,\Omega \tag{9}$$

Using a theoretical resistance of 0.0128 ohms per wire and a load resistance of 13.4 ohms, a model in PSpice was created and the node voltages were calculated as shown in Fig. 9.

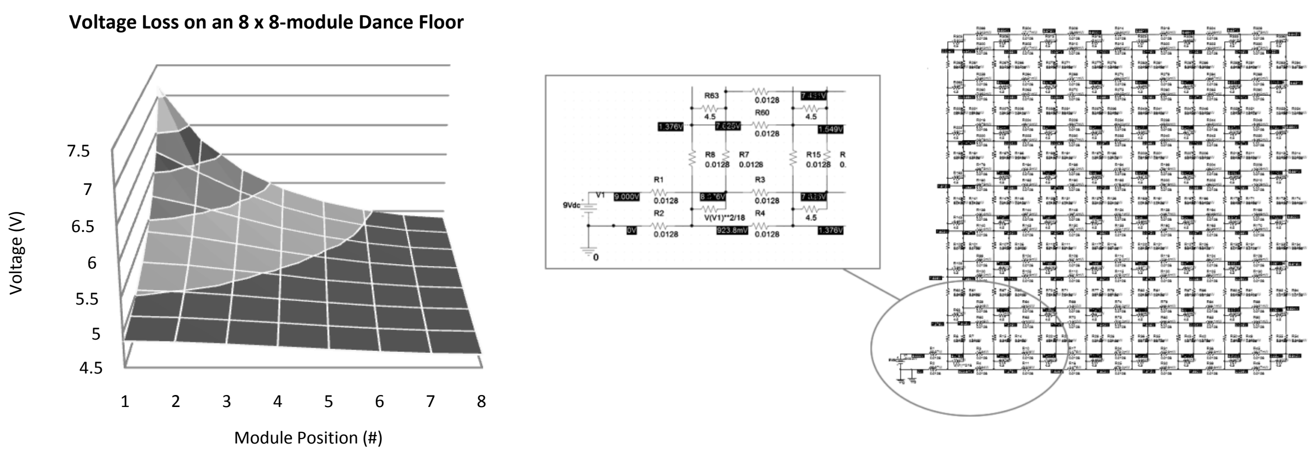

Fig. 9. PSpice simulation of the dance floor power distribution using 16 AWG copper cables. The 3D plot of the voltage at each module demonstrates the high voltage loss seen when transmitting high current, low voltage DC power over long cable distances.

The 3D plot in Fig. 9 demonstrates the unfeasibility of a low voltage DC power bus. The resistances the 16 AWG cables incur introduce high voltage losses as the high currents across them create significant voltage drops throughout the floor. The cables, rather than acting like ideal conductors, look more like resistor dividers; furthermore, the simulation calculated a total current draw at the main power supply of 72 A. This far exceeds the maximum safe operating current for 16 AWG cable at the current lengths.

To resolve these issues higher gauge wire could be used. This would result in lower resistance in the wires and also allow higher currents to be delivered safely. However, larger gauge wire is expensive and 16 AWG wire was already available for free. Larger wire is also heavier, and since portability was a key design goal of the project, it was dismissed. Another option was to use higher voltages. A higher DC voltage could be used in the floor to further reduce resistive losses, since power is proportional to the current squared. However, this too was dismissed due to cost since DC voltage regulators rated for high voltages are somewhat expensive.

The solution that was reached was to use mains voltage, 120 VAC, for the main power bus. This offered some very significant advantages. First, 16 AWG cable could easily be used to send power throughout the floor due to the lower currents at higher voltage. This was a large cost factor as it allowed free cables to be used as well as smaller connectors and it also slightly reduced the weight of each module. Second, 120 VAC allows the use of COTS power adapters to regulate power down to 9 VDC for the modules' electronics. This further reduced cost and design time by allowing the use of low-cost, commercially-available equipment rather than having to design and build custom voltage regulators.

The use of mains voltage, however, also required serious consideration about safety. The possibility of short-circuits inside the dance floor is not as important at low voltage DC as it is at 120 VAC. Therefore, the main power bus was fused with a 15 A fast-blow fuse to prevent shorts from causing safety hazards. Furthermore, large keyed Molex® connectors were used to connect modules together which insulate each pin with plastic to prevent accidental shorts, incorrect pin alignment, and the possibility of users connecting the dance floor to other commercial appliances.

By minimizing the risks and maximizing the benefits of 120 VAC, a mains voltage bus was used to reduce power loss, and thus increase efficiency, and also reduce the cost per module of the dance floor. A block diagram of the entire dance floor power system is shown in Fig. 10.

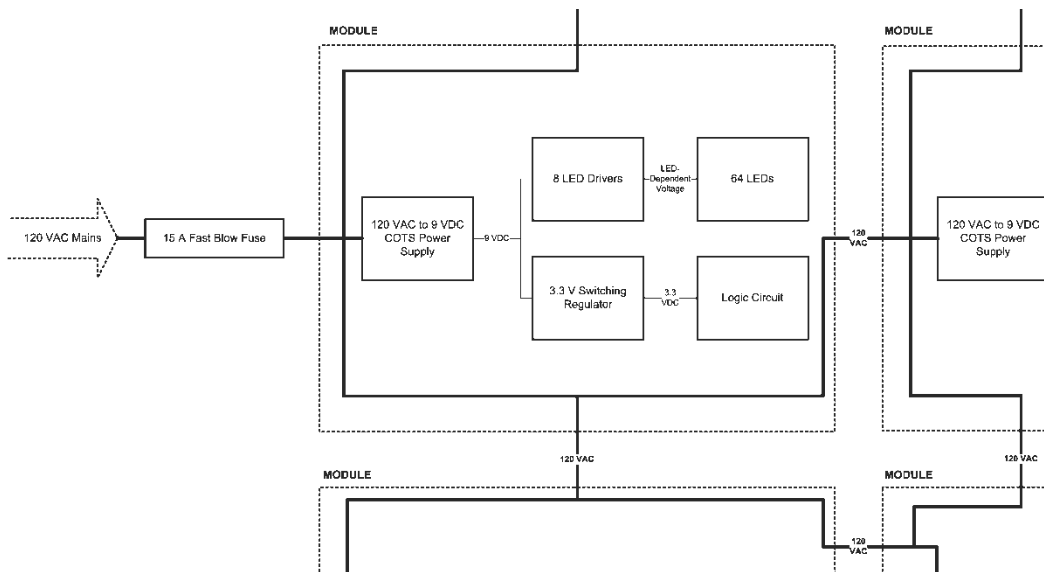

Fig. 10. Block diagram of the entire dance floor power distribution and regulation system. The diagram shows how the modules are interconnected and how the modules internally regulate power for the various devices.

V. Operation/Testing/Verification

At this point, no operation testing or verification has been performed. The printed circuit boards are still in the design phase and a soldering failure on the first prototype circuit board prevented testing of the power systems. Real-world data are forthcoming.

VI. Discussion/Conclusions

By combining the benefits of high-voltage AC to reduce cable losses and cost with switching DC regulators to reduce heat dissipation and further reduce power loss a highly efficient power system was implemented in the dance floor. Low-voltage DC power and linear voltage regulators were investigated and found inferior due to high power losses and heat dissipation, both of which were undesirable for the dance floor's application. In the design, switching regulators raised the efficiency of the logic circuit power supply from 37% to 75% and high-voltage AC power was distributed to the modules to reduce the current flowing through the cables and thus reduce cable losses. The project also demonstrated the benefits of using COTS equipment to reduce cost and development time.

However, the current findings are unconfirmed since a physical device has yet to be built. While theory suggests great benefits, lacking real-world results means a definite conclusion cannot yet be reached.

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