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Fostering Intuitive Minds for Power System Design

A case study showing how a design project can be used to provide intuitive insight when teaching power system design

ONE OF THE MOST CHALLENGING ASPECTS OF ENGINEERING EDUCATION is to give students an intuitive feel for the systems they are studying. Historically, engineering schools have excelled at providing their undergraduate students with a strong background in the basic sciences and the theoretical fundamentals of engineering. Such a background has been, and continues to be, crucial. But while paper and pencil exercises can be quite useful for highlighting these fundamentals, they often fall short in imparting the desired intuitive system insight. Yet such insight can be crucial, particularly as a new engineer moves from straightforward analysis into the domain of design. To help, this article provides a case study example of how a design project can be used to provide such intuitive insight into both basic power system operation involving power flow and contingency analysis as well as more advanced topics involving an hourly locational marginal price (LMP) power market. This design project is based upon one developed by the author that is included in the *Power System Analysis and Design* textbook (third edition), and it is solved using the PowerWorld Simulator software.

The Starting Point

In the design project the students are asked to develop the least-expensive option for

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upgrading a 37-bus, nine-generator power system so that for the specified loading of 833 MW the system will have no flow or voltage violations for either the base case or for the set of all line-outage contingencies. A one-line of the system, which was derived from the transmission grid of an actual urban area, is shown in Figure 1. In deciding on the size of the power flow case for this project the goal was to present the students with a sufficiently large case so they could better understand the complexities associated with interconnected power system design, yet one small enough to prevent them from being completely overwhelmed. Thirty-seven buses seemed like a good compromise, with the added advantage that the one-line could be completely displayed on a computer screen with reasonably sized components. The students were provided with a completely defined power system model and one-line, including generator cost characteristics, and the set of 57 single transmission line and transformer outage contingencies. The system contained 345-, 138-, and 69-kV buses.

Key to providing the students with intuitive insight into the operation of such a power system is the use of a user-friendly, highly interactive graphical user interface (GUI) coupled with a robust power system analysis package. With the GUI students could easily make changes to the system and then immediately see the impacts of their changes reflected on the one-line. The use of animated power flow arrows also helped to convey how power flows from the generators through the transmission network to the loads. Also, tabular displays of many different quantities such as bus voltages and loads, generator outputs, and line flows could be used to supplement the one-line values.

To better replicate actual system operation, in which power system operators and engineers work to insure that there are no violations in either the base case or for a set of statistically likely contingencies, the design project required the students to perform a full contingency analysis solution. If done manually this would have required the students to sequentially open each of the 57 individual lines and transformers, solve the power flow, check for violations, and then reclose the device. While performing such a procedure manually once or twice might have some pedagogical benefit, it would rapidly become tedious during a design process. Rather, the students were encouraged to use the built-in contin-

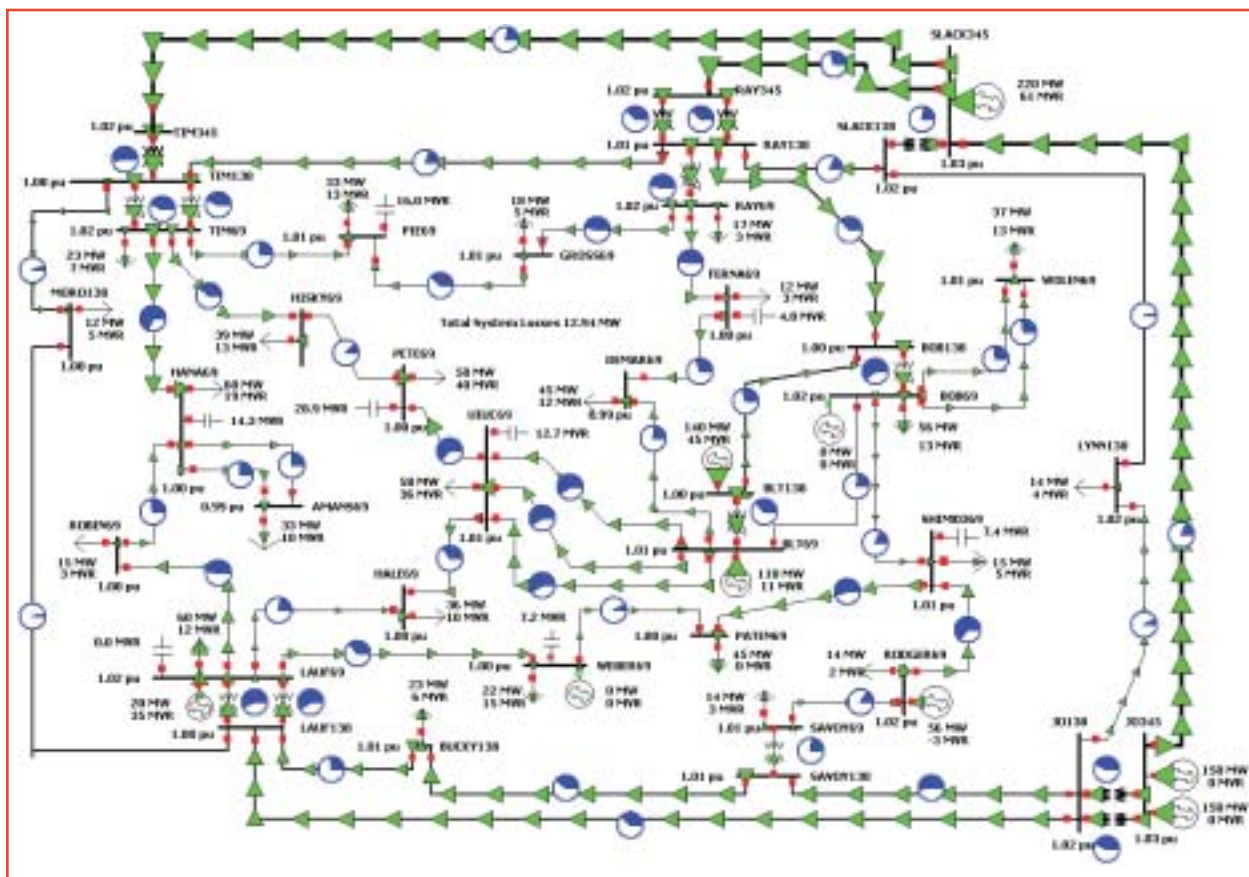


figure 1. Initial one-line for the 37-bus design case.

gency analysis functionality, as shown in Figure 2. With a click of a button the full contingency analysis set was run (in about a second), with the results displayed based upon the severity of the violations. The case was designed so it had a total of seven initial violations caused by three different contingencies with all the violations in the western (left) portion of the system. Of the seven, six were transmission line overloads and one was a low bus voltage (defined as being less than 0.90 per unit).

To make the project assessable to students with only a background in power flow, but not necessarily in economic dispatch or optimal power flow (OPF), for the initial project the real power outputs of all the generators were assumed to be fixed, with any change in losses picked up by the system slack bus (bus SLACK345 shown in the upper right-hand portion of the one-line). This simplification is relaxed in the more advanced project described in the later part of this article.

Upgrading the Grid

The heart of the design project was to determine the least expensive set of system upgrades that would remove all of the contingent violations. Of course, in real life a design engineer would be presented with a wide variety of different design possibilities, such as upgrading existing lines, constructing new lines, constructing new generation, adding power system

control devices such as switched capacitors or FACTS, implementing interruptible load control, or moving substation load through changes in the distribution system. However, simultaneously many of these possibilities would be eliminated through considerations such as cost, right-of-way restrictions, public opposition to new construction, and environmental constraints.

To make the student design project manageable yet still interesting, the choices were limited to adding a new 138/69-kV transformer and associated bus work and building new transmission lines on some of the eight right-of-ways identified using the yellow lines in Figure 3. Cost information was provided for two different-sized transformers (101 MVA and 187 MVA), and three different types of line conductors for potential 69-kV lines (Partridge, Lark, and Rook conductor types), and three for the potential 138-kV line (Lark, Rook, and Condor types). The assumed costs for each of the right-of-ways are shown in Table 1.

The students were then responsible for determining the parameters for the new lines using the conductor type, an instructor-provided transmission tower configuration, and the right-of-way length. Providing the students with only the conductor type and tower configuration requires that they derive the model parameters, providing a nice reinforcement of transmission-line modeling concepts. For this article a symmetric

tower configuration was assumed with 5-ft conductor spacing. In addition to minimizing construction costs, the project also required consideration of the savings associated with any decrease in system losses over the next five years, again with the simplifying assumption that the load stays fixed over the entire time period

Since this project was designed to require at least two new system devices, the number of design possibilities is relatively high. For example, if one just considers combinations of two new transmission lines with each having three possible conductor types, the number of possibilities is equal to 168. While the software environment allowed students to easily add new lines and transformers, nevertheless, students who blindly attempted all possibilities had to do a good amount of analysis.

Hence, one of the project goals was to have the students realize that an understanding of the “why” behind the system

table 1. Total costs for the different right-of-ways (US\$ in thousands).

Right-of-Way	Mileage (Miles)	ASCR Conductor Type			
		Partridge	Lark	Rook	Condor
HANA-HISKY	7.0	680	785	890	—
HANA-PETE	5.5	545	627.5	710	—
AMANS-UIUC	5.7	563	648.5	734	—
AMANS-HALE	4.5	455	522.5	590	—
AMANS-LAUF	7.3	707	816.5	926	—
AMANS-PETE	4.5	455	522.5	590	—
TIM-HANA	11.0	1040	1205	1370	—
MORO-HANA ^a	8.3	—	2581	2664	2747
MORO-HANA ^b	8.3	—	2861	2944	3027

^a138-kV line with a new 138/69-kV, 101-MVA transformer at MORO

^b138-kV line with a new 138/69-kV, 187-MVA transformer at MORO

violations could help to guide them in limiting the number of design possibilities they needed to consider. For example, referring to Figure 3, the system parameters were specifically chosen so a contingent outage of the TIM69 to HISKY69 line would cause an overload on the UIUC69 to PETE69 line,

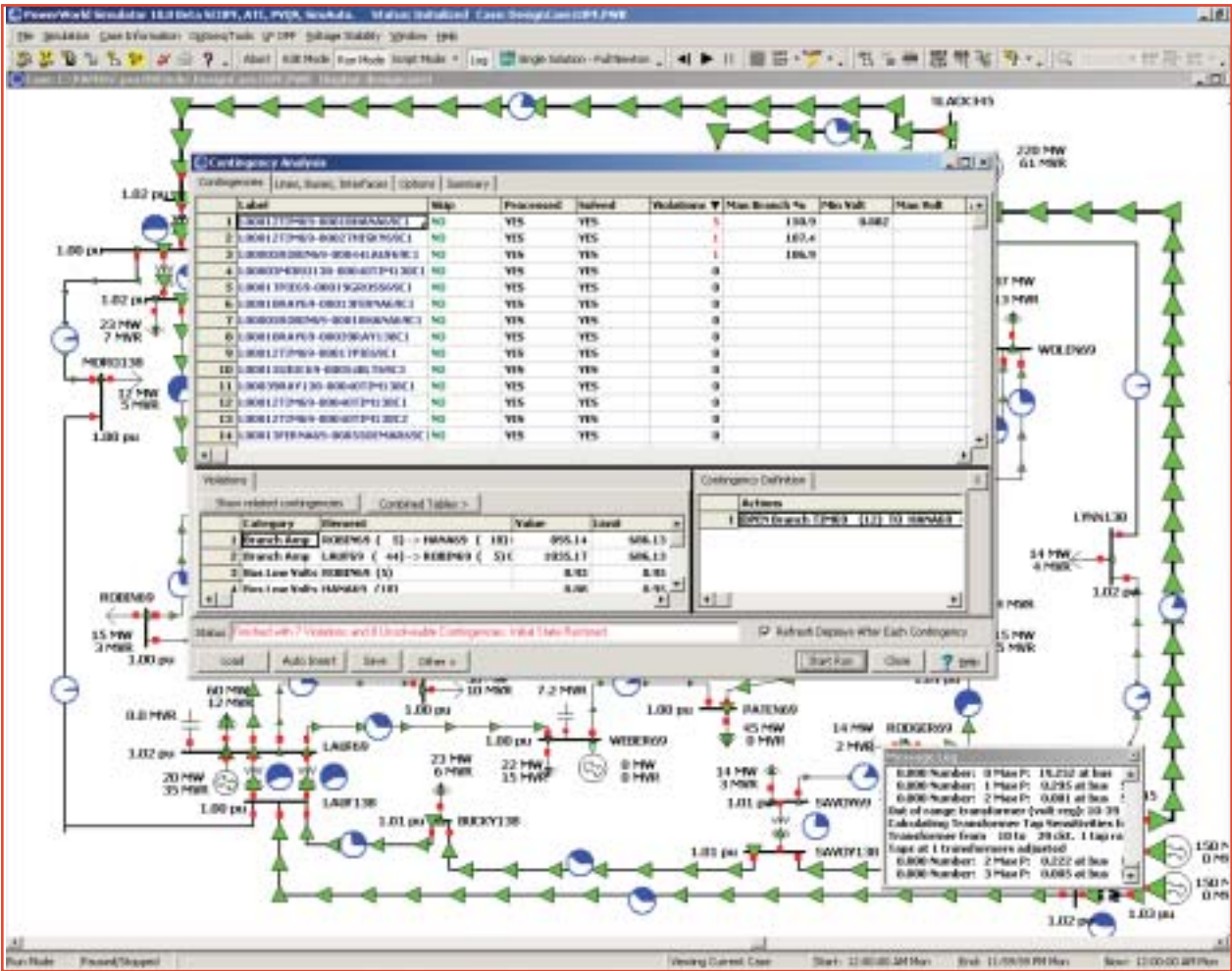


figure 2. Integrated contingency analysis.

Key to providing the students with intuitive insight into the operation of a power system is the use of a user-friendly, highly interactive graphical user interface.

which is now radially feeding the PETE69 and HISKY69 substations. Since the supply into these two substations is radial during the contingency, the only way to eliminate the line violation is to construct a new line using one of the three available right-of-ways that join to one of the affected substations.

If the project objective was limited to just removing the contingent violations, then a good solution approach would be to order all the double-line combinations that contained one of the above three right-of-ways based upon their construction costs. Then, starting with the least expensive (AMANS-PETE and AMANS-HALE using Partridge conductors), contingency analysis should be performed on each one until a combination was found that eliminated all the violations. For this project list, it would only require a single entry since the AMANS-PETE/AMANS-HALE combination satisfies this constraint.

However, the project also required consideration of the impact the new transmission would have on system losses over the next five years. The importance of the losses of course depends upon the assumed cost of replacement power. Here, a value of US\$50/MWh was used, resulting in a five-year savings of US\$2.19 million per MW decrease in these losses. This completely changed the problem, requiring the student to perform a more detailed analysis. Starting with premodification losses of 12.21 MW, Table 2 presents the new losses resulting from various combinations of new lines, with the three columns containing possible line additions required to remove the TIM69-HISKY69 contingency violation. Note that several of the double-line additions did not correct all the violations, but most did.

If the conductor type were restricted to Partridge (i.e., the

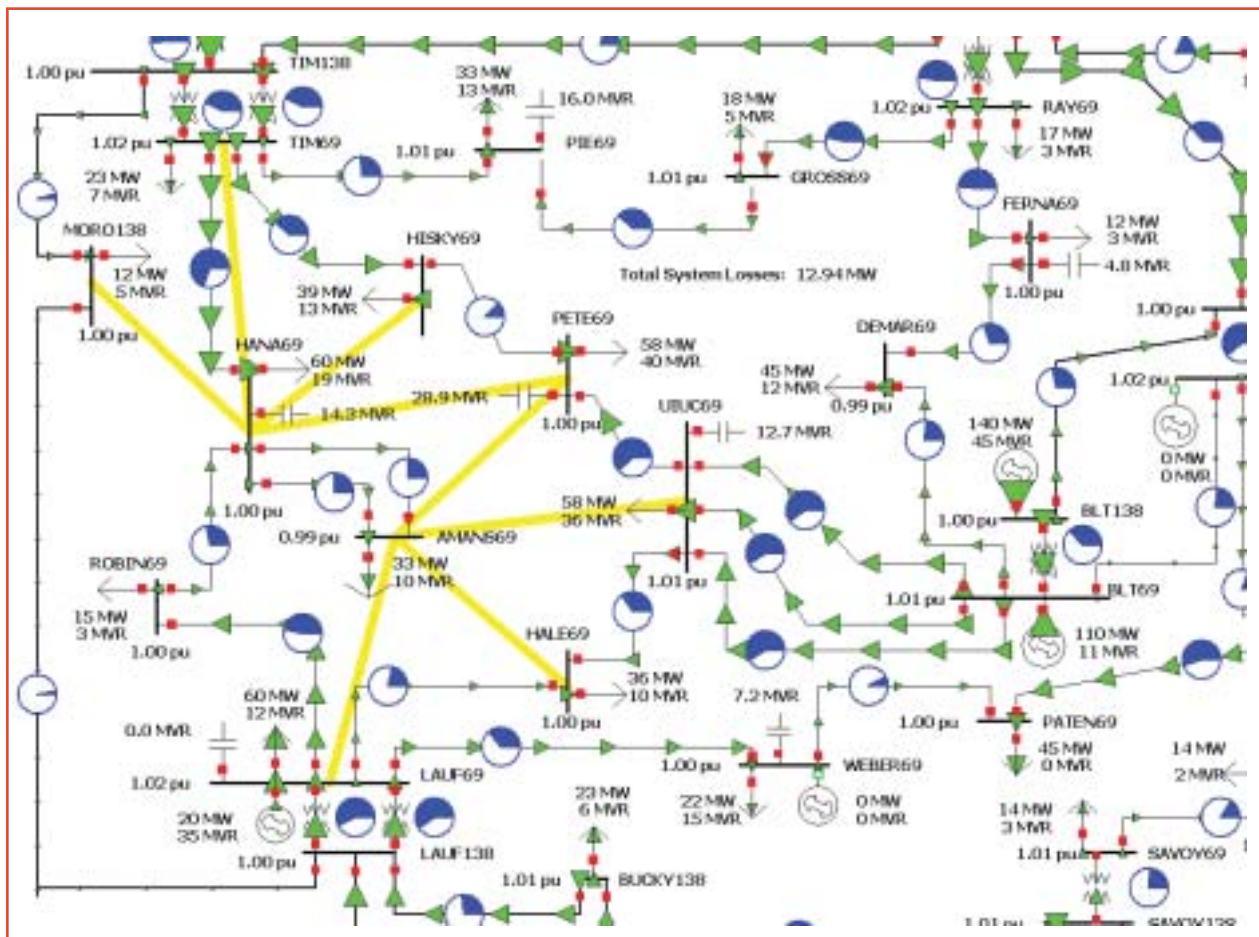


figure 3. Available new right-of-ways.

One of the project goals was to have the students realize that an understanding of the “why” behind the system violations could help them in limiting the number of design possibilities.

least expensive), the optimal design would now require adding a 69-kV line from AMANS-PETE and a second from AMANS-UIUC. This combination would have construction costs of US\$1,018,000 but losses savings of US\$1,226,400, resulting in a net savings of US\$208,400 over the five-year period! When the other two conductor types are considered, the optimal solution actually is to build the line from AMANS-UIUC using the more expensive but less lossy Rook conductor and to use Partridge with the AMANS-PETE line. This change slightly increases the construction costs but decreases the losses to 11.48 MW for a net five-year savings of US\$409,700.

Classroom Application

The case study results presented here are based upon this design project being assigned to 40 students in a senior-level power system analysis class as part of the homework portion of their grade. Approximately 90% of the students were electrical engineering undergraduates while the remainder were first-year graduate students. Each student was responsible for developing their own optimal design. The students were told they could certainly discuss the problem amongst themselves but needed to turn in their own work.

A potential problem with many classroom assignments is excessive collaboration, to the point of copying, by some students. In order to minimize this, each student was given a slightly different variant of this design project with the assignments differentiated by the assumed symmetrical conductor spacing. The spacings ranged from 4.25 ft to 14.5 ft in 0.25-foot intervals, resulting in a maximum variation of the line reactance values between students of approximately 25%. The line resistance values, of course, remained unchanged. This change in the modeled line reactances did slightly alter the system losses and for the high reactance models did result in several additional line combinations not being able to remove all the violations. But it did not change the optimal design.

Overall, about 30% of the students correctly identified the optimal design including the correct conductor choice. Another 45% of the students correctly identified the two new lines but chose to build both using either all Rook or all Partridge

conductors (with the students split evenly between the two). About 12% of the students choose to build the near optimal AMANS-UIUC and HANA-PETE lines with one student mentioning this choice might be more politically palatable to the residents living close to the AMANS substation since it avoided building two new lines at a single substation. All of the student designs satisfied the contingency constraints with

table 2. New system losses (MW) for double transmission line additions using the Partridge conductor for the 69-kV lines and Lark for the 138-kV line.

		First line	
Second Line	HANA-HISKY	HANA-PETE	AMANS-PETE
HANA-HISKY	—	11.85 ^a	11.80
HANA-PETE	11.85 ^a	—	11.79 ^a
AMANS-UIUC	11.67	11.66	11.65
AMANS-PETE	11.80	11.79	—
AMANS-HALE	11.82	11.82	11.79
AMANS-LAUF	11.58 ^a	11.56 ^a	11.59 ^a
HANA-TIM	11.72	11.71	11.66
HANA-MORO	10.93	10.94	10.93

^a Did not remove all contingency analysis violations

only one choosing the least-expensive construction cost alternative. The students were told the project would require approximately 15 hours to complete, but most reported it took them considerably less time.

A large number of the students immediately dismissed the new MORO-HANA 138-kV line because of its high initial costs. With losses priced at US\$50/MWh this line was not an optimal solution, but it was actually much closer to being optimal than most realized. Using the Condor conductor for a new MORO-HANA 138-kV line, coupled with a new AMANS-PETE 69-kV line, would result in new losses of 10.76 MW. With losses priced at US\$50/MWh this design has a net cost of US\$27,000 over the five-year period. But if the assumed cost of losses were increased to US\$64/MWh or higher, then this design actually becomes optimal. This analysis can be helpful in pointing out to the students that high initial cost designs may actually be the best over the long-term. The analysis also presents a second option for problem variants—different students could work the same design using different assumed costs for losses.

Expanding the Project

The advantage of performing a design assuming a fixed system load and generation dispatch is it limits the number of variables the students need to consider and opens the problem to a wider group of students. But the disadvantage is that power systems are time varying with significant changes occurring in both the load and generation. Therefore, for more advanced students the project could be expanded to include a design based upon the results from a security constrained optimal power flow (SCOPF) either for a fixed system load or for a time-varying load.

The goal of the SCOPF is to obtain an “optimal” dispatch of the system generation (and possibly other controls) subject to the requirement that the solution not have any violations in either the base case or in any of the contingencies. Once the SCOPF has been solved, the marginal cost of supplying electricity to each bus in the system (i.e., LMPs) can be computed. While the definition of “optimal” may vary, a common SCOPF objective function is to minimize the total system operating cost subject to the aforementioned constraints. The extension of this design to include the SCOPF is facilitated by the project software including an integrated SCOPF algorithm.

The use of the SCOPF does not completely eliminate the

need to perform system design since, regardless of the generator outputs, the line from UIUC69-PETE69 is still overloaded during the TIM69-HISKY69 line outage contingency. Without at least some new transmission the only way to remove this overload would be to perform load shedding. Still, the SCOPF could lessen the need for system transmission upgrades since some of the contingent violations could now be managed by optimally redispatching the generation.

For example, by using the SCOPF all the design case contingent violations can now be eliminated through the addition of a single 69-kV line from AMANS to PETE; that is, the lowest “construction cost” design. But a consequence of this design is it requires a generation redispatch away from the economic dispatch solution. This redispatch causes the bus LMPs to vary with high prices in the western portion of the system, and low prices elsewhere. Figure 4 shows a contour of the bus LMPs, with the values ranging from a low of US\$23/MWh to a high of US\$43/MWh. The total modeled operating cost with this design is US\$16,125/hr. If the second line proposed above is built, from AMANS-UIUC, the operating cost drops to US\$16,027/hr while the bus LMPs equalize at US\$26/MWh.

The inclusion of the SCOPF results in a more difficult but also more realistic design process. It also opens the door for

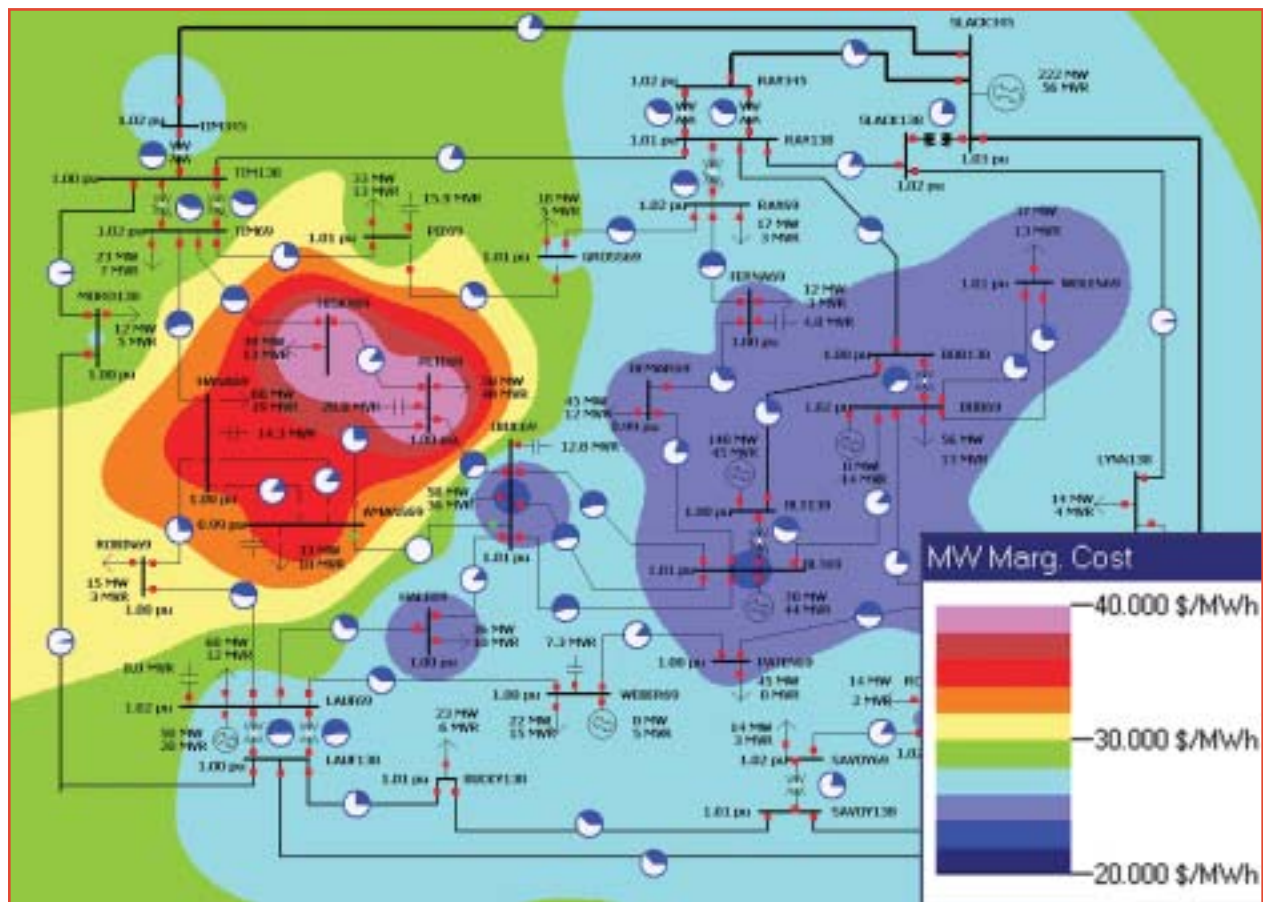


figure 4. Contour of bus LMPs with only the new 69-kV line from AMANS-PETE.

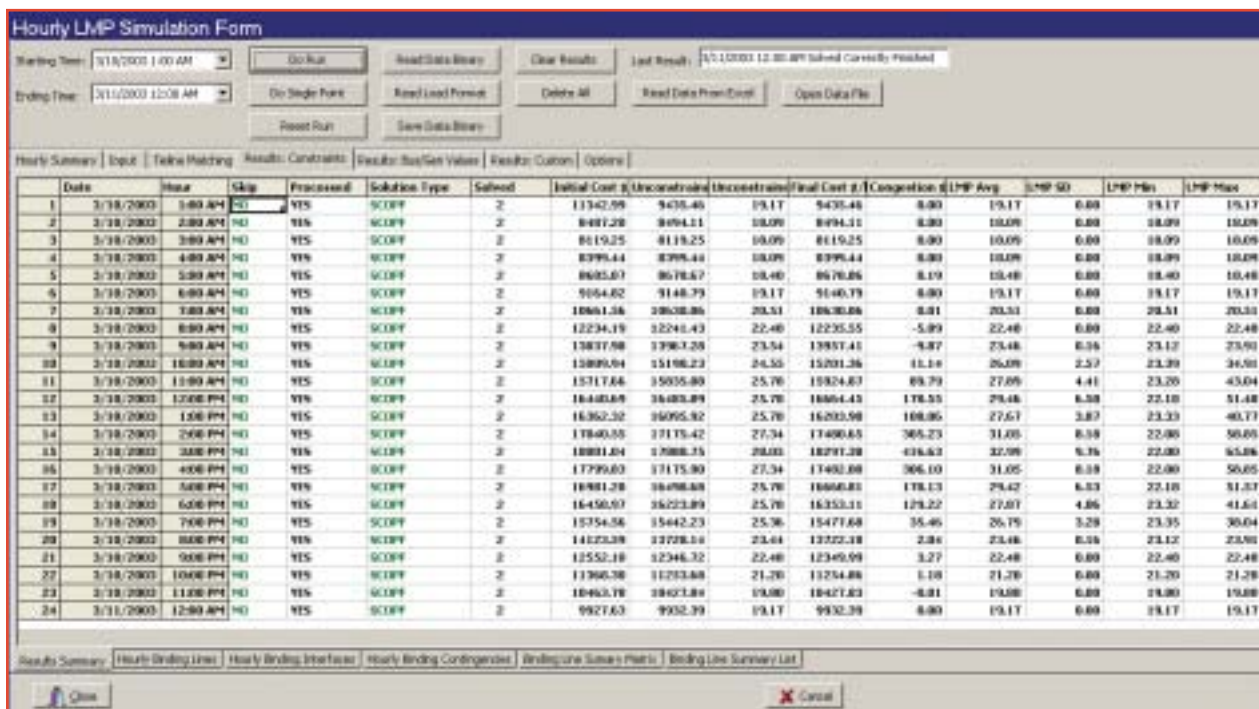


figure 5. Hourly SCOPF analysis of the design case.

an effective classroom discussion of the issues associated with restructured power market design and operation. For example, in an LMP-based market, in which generators are paid based upon the LMP at their bus, one of the goals of high LMPs is to send a signal to generation companies of where to site new generation. In the case of Figure 4, the best locations for new generation, at least from an LMP viewpoint, would be at the HISKY and PETE substations. New generation at either of these sites would help to mitigate the overloads in the area. But the overloads could also be eliminated through the addition of a new transmission line, eliminating the high LMPs in the process. What is the right balance between new generation and new transmission is ultimately a market and societal decision, but it is certainly a good topic for classroom discussion.

A final extension of the design project could be to move from considering just a single-load snapshot to a load-variation profile. The inclusion of this load variation would help to emphasize to the students that power system engineers need to consider a wide variety of different operating conditions. While one could perform such analysis manually by looking at a set of load snapshots, it would be much more convenient to have the software manually change the load, performing contingency analysis or the SCOPF at each load level. Figure 5 shows an implementation in the design project software to automatically vary the load, in this case over the course of 24 hours. During this time period the load varied between 470 and 900 MW, while the bus LMPs ranged from US\$18/MWh to US\$66/MWh. The solution time for this 24-hour study was about 20 seconds, low enough to continue to allow interactive design.

Design should be an essential aspect of a power system education. The appropriate level of detail for a design project depends, of course, upon the level of the students and the time available within the course. This case study article has presented a design case that would be appropriate for higher-level undergraduates and has also shown how it could be extended for use in introductory graduate-level courses.

For Further Reading

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Biography

Thomas J. Overbye is an associate professor of electrical and computer engineering at the University of Illinois at Urbana-Champaign. He received his B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Wisconsin-Madison in 1983, 1988, and 1991, respectively. He was employed with Madison Gas and Electric Company from 1983 to 1991 where he worked to help develop their real-time power system analysis software. He is also the original developer of PowerWorld Simulator and a co-founder of PowerWorld Corporation. His research interests include power system analysis, restructuring, and visualization.

