Apply Dynamic System Rating as a Proactive WAMPACS

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Traditionally, wide-area monitoring, protection, and control systems (WAMPACS) are used for reacting (tripping) to prevent cascading outages from problems such as system stability (angular and voltage), frequency, and other system alert, emergency, and extreme events. A recent application of WAMPACS for preventive and operational purposes has been introduced: dynamic system rating (DSR). DSR combines thermal dynamic line ratings (DLR) that raise the power transfer for line and bus loading, dynamic power rating (DPR) monitoring voltage and angular stability, and optimal power-flow controllers (OPFC) for line flow-management control.

As line power transfer and bus loading increase, voltage and angular stability margins decrease. Compounding the issue is the penetration of inverter-based resources (IBRs), which produce variable voltage and current outputs and provide less power-system inertia. Using traditional transient-stability determinations, these factors introduce errors and unnecessarily conservative margins. Synchrophasors (PMU data) yield precise and real-time determination of transient stability in line and bus locations where exists congestion and large penetration of variable IBR renewable sources. This PMU data provides precise, transient-stability, power-flow limit determination, with contingency analysis. Thus, maximum safe power flow occurs on lines and load buses in the PMU-monitored area.

This paper explores the fundamentals of grid congestion and its negative impacts, DSR functional building blocks, DSR calculation methods, power angle, equal-area contingency analysis, voltage stability curves, and power-flow redirecting and redispatch tactics to improve transient stability.

I. Introduction

Historically, the power grid has been a static resource. Power flow from generation to load centers is via a transmission line with impedance Z, and load parameter S, as shown in the simplified system of Fig. 1.

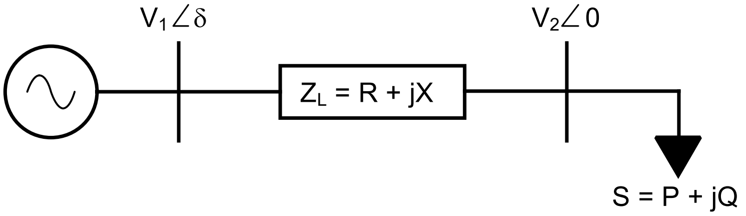

Fig. 1 Simplified power system a generation source, line impedance and load

Operators understand the line parameters, both impedance and physical construction, and set limits on power dispatch. Some flexibility exists in power dispatch for all ambient conditions for responding to variable loading, S, in all seasons. A wide-area monitoring, protection, and control system (WAMPACS) senses grid voltages and currents. When the grid exceeds set limits the WAMPACS acts to return the power grid to proper operation and prevent cascading outages. A WAMPACS monitors and controls voltage (V_1 and V_2) amplitude, angle, and frequency; it responds to other system alerts, emergencies, and extreme events.

Engineers have designed the power system with large margins, based upon worst-case assumptions. Rather than relying on this static model, significant benefits come from reimagining the power grid, recognizing its dispatchable capabilities. Enhanced WAMPACS monitoring and automation unlocks value from the existing power grid. The WAMPACS is a grid-enhancing technology (GET). GETs promote better utilization of the existing transmission system by managing transmission congestion and increasing line-utilization rates [1]. Investing in fuller utilization of the grid promotes more efficient usage right now and ensures that future investments in infrastructure are fully realized.

GETs provide a solution to the challenges in delivering electric power safely, reliably, and economically.

a) Improving power-grid capacity

Costs continue to increase as utilities experience load growth and as more renewables are added to the grid. An additional 40–90 GW of solar on the grid per year and 70–150 GW of wind per year of renewable energy are expected to be built in the next five to ten years [2]. This is more than four times the current annual deployment levels for each technology. New transmission is needed, but costs, permitting, and construction timelines delay the implementation for years. GETs can provide more capacity in months, not years, and at a fraction of the cost of building new infrastructure.

b) Congestion and renewable-curtailment relief

The transmission grid is experiencing record levels of congestion costs and interconnection delays. These effects are significant:

- In the US, the National Renewable Energy Laboratory has reported that grid capacity must triple to achieve zero carbon by 2035 [2]
- US consumers paid $21 billion USD in congestion costs in 2022 [3]. These costs will rise as more renewables become available
- More than 1.4 terawatts of renewable energy projects are stuck in interconnection queues, waiting to connect to the grid [4], [5]
- Europe’s goal is to reduce greenhouse-gas emissions by at least 55% by the end of the decade compared to 1990 levels and source 38%–40% of its energy consumption from renewable energy [6]
- Australia is preparing for the clean energy transition with 67 GW of renewable energy projects in the interconnection queue. However, congestion has prevented much of that capacity from becoming operational [7]

The shift to renewable energy sources cannot be realized without expanding transmission capacity, which already is lacking, resulting in congestion and record high electricity prices.

System operators must limit power flow on transmission and distribution lines, curtailing available power from connected renewables. Thus, power needed for a growing load base cannot be delivered. GETs alleviate the problems of congestion and curtailment.

c) GETs system benefits

GETs provide several system benefits. These benefits include the following [1]:

- Situational awareness for safer, real-time operation
- Asset deferral, to give time to implement longer-term solutions
- Increased grid resilience
- Asset health monitoring

Deploying a WAMPACS improves existing transmission system reliability because system operation remains within safe limits. This can alleviate building new transmission-system infrastructure in certain areas.

II. Static line ratings

Historically, a utility operated their power system with static line ratings (SLRs). System operators make dispatch decisions to maintain safe operating conditions, based on IEEE Standard 738 “IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors” [8]. These are thermal ratings that use conservative assumptions about the transmission-line operating environment, including the following:

- Static weather conditions
- Average wind speeds and direction
- Average ambient temperatures
- Solar conditions for summer and winter

Because these are averages, there are times when the real ratings based on actual conditions differ from the static ratings. Less rating leads to thermal damage and sag, while a greater rating could transfer more power. SLRs are inflexible and cannot take advantage of the favorable rating conditions that occur for many hours of the year.

III. Dynamic System Rating WAMPACS

Today, incorporating grid-enhancing technologies in a WAMPACS creates a dynamic system rating (DSR). DSR increases grid capacity and optimizes the power flow across the grid. DSR combines the following methods to create a comprehensive solution to power-flow optimization:

- Dynamic line rating (DLR) thermal assessment for increased transmission capacity
- Dynamic power rating (DPR) monitoring voltage and angular stability
- Optimal power-flow controllers (OPFC) for line power-flow management control

a) Dynamic line ratings (DLR)

Dynamic line rating (DLR) offers real-time and forecasted transmission-line ratings. This method uses two techniques:

- Sensor measurements and computational analysis of critical conductor properties including conductor sag, blowout, and temperature
- Computational fluid dynamics

DLR calculates a line thermal capability by creating an advanced thermal assessment from sensors placed along the power line or line computer modeling, and from predicted weather conditions. Fig. 2 shows how DLR increases the line power flow limit by increasing the line current limit.

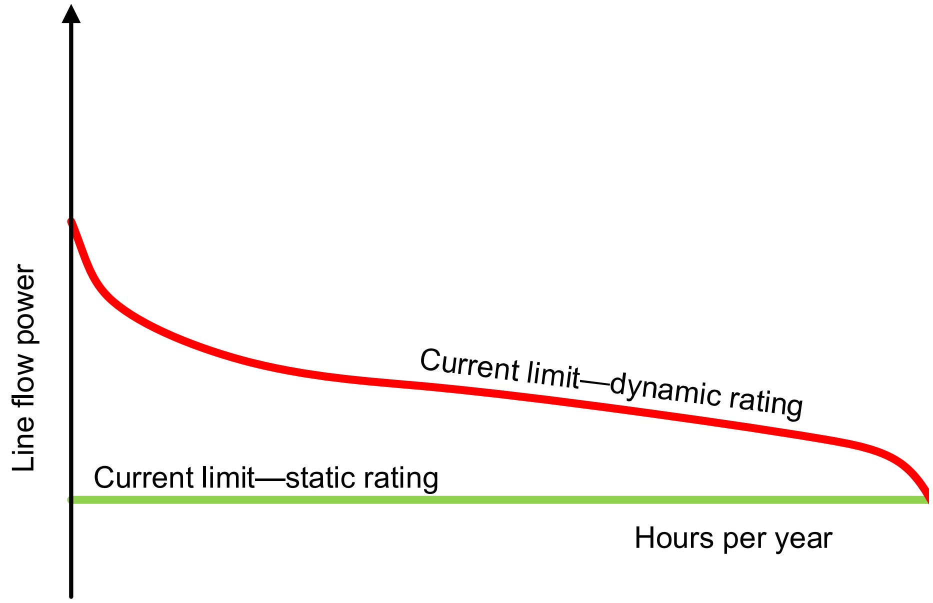

Fig. 2. Thermal-limit assessment

b) Dynamic power rating (DPR)

Dynamic power rating (DPR) performs real-time monitoring of angular stability and voltage stability. Angular instability is generator-driven, as opposed to voltage instability, which is load-driven.

i. Angular stability

DPR produces an angular stability assessment using the equal-area criteria (Fig. 3) with contingency for the simplified power system shown in Fig. 1. The calculation includes placing a 3-phase fault at a line terminal and then establishing an N – X worst-case, line-out scenario to arrive at the safe line operating angle, $\delta_{0,New}$, for the safe line rating.

The electrical power follows the power-transfer formula:

$$P_{E1}(\delta) = \frac{V_1 \cdot V_2}{X_{T1}} \cdot \sin\delta = P_{M1} \cdot \sin\delta \qquad (1)$$

where

P_{E1} is the electrical power

P_{M1} is the mechanical power

V_1 is the transmitting line-terminal voltage

V_2 is the receiving line-terminal voltage

X is the line Impedance (neglect resistance R)

sin δ is the sine of the line angle

The calculation begins with all lines in (upper, green line) with operating position at Location 1, δ_0. Next, apply a three-phase fault (the lowest, red line) to arrive at Location 2. The generator speed increases to supply fault current, and the WAMPACS clears the fault at Location 3, δ_C. A new operating position is on the middle line at Location 4. The generator continues to speed for a moment until the system issues a control-reduction signal at Location 5, δ_F, decreasing the operating power to the new angle at Location 6, $\delta_{0,\text{New}}$.

In systems with small inertia, angular stability is a concern when the DLR method maximizes the power through the line. DPR assessment allows or disallows larger, DLR-permitted, line power flow. Loss of angular stability causes the system to go out of step and separate. To protect angular stability, the WAMPACS separates the minimal amount of generation, and to protect voltage stability, it separates the minimal amount of load.

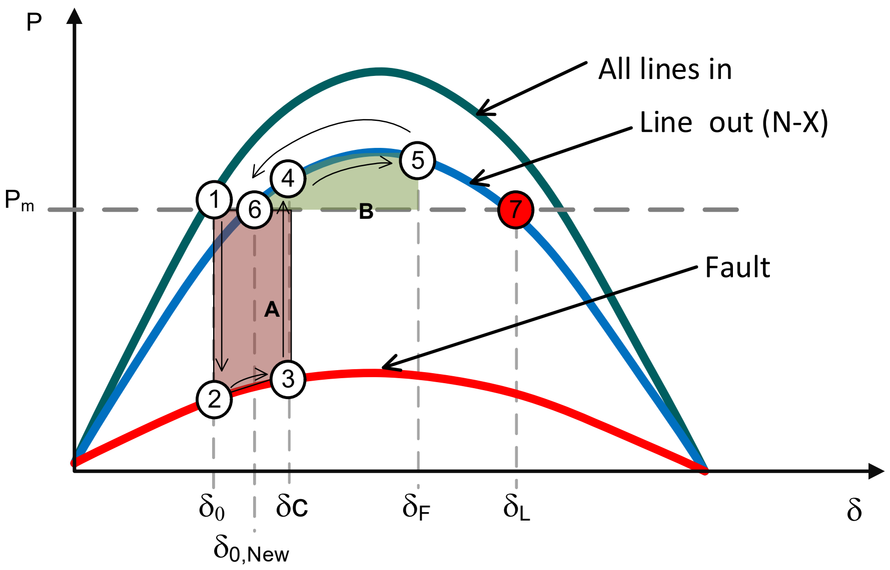

Fig. 3. Angular-stability limit assessment

ii. Voltage stability

In addition, DPR produces a voltage-stability assessment for the associated lines under evaluation.

Voltage stability is a factor of source impedance, line/power corridor impedance and load impedance. The power delivered at the load is proportional to the system voltage, as shown in (2):

$$P + jQ = V_2 \cdot \left(\frac{V_1\angle\delta - V_2}{R + jX}\right)^* \quad (2)$$

The active and reactive power transfer is a function of the generator- and remote-bus voltages (V_1 and V_2), the line impedance ($Z_L = R + jX$), and the voltage-angle difference between the generation and load, δ. Real-power and reactive-power quadratic equations in (3) and (4) develop the P-V curves, or “nose curves” [9].

$$P = \left[(V_1 \cos\delta - V_2) \cdot \frac{R}{R^2 + X^2} + V_1 \sin\delta \cdot \frac{X}{R^2 + X^2}\right] \cdot V_2 \quad (3)$$

$$Q = \left[(V_1 \cos\delta - V_2) \cdot \frac{X}{R^2 + X^2} - V_1 \sin\delta \cdot \frac{R}{R^2 + X^2}\right] \cdot V_2 \quad (4)$$

Fig. 4 shows the nose curves [10]. If load increases beyond reactive support, voltage begins to drop. As the line/power corridor impedance increases, the voltage drop across it increases, contributing to the voltage reduction at the load. A point is reached after which the voltage collapses (A2 and B2).

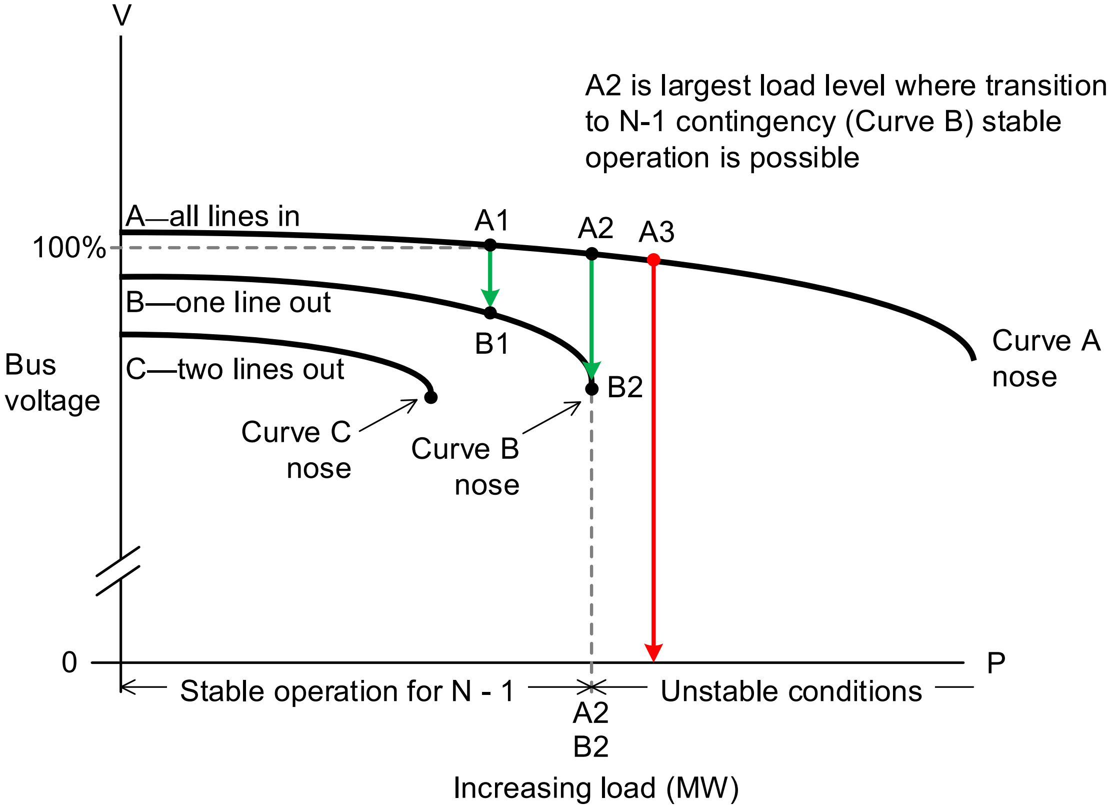

Fig. 4. Voltage-stability margins in contingency conditions

Power consumed increases along Curve A. Operating at Location A1 is stable when one line is removed, and operation continues at Location B1. Location A2 is the limit of load power consumption because operation is stable at the one-line-out Location B2. Operation at Location A3 is not allowed by the DPR calculations because the system becomes unstable when one line goes out. This set of P-V curves illustrates that for the baseline conditions of Curve A, the voltage remains relatively steady as local load increases. System conditions are secure and stable to the left of Location A1. After a contingency occurs, (a transmission line trips) the new condition is Curve B, with smaller voltages. This is because the power transmitted from the remote generators is now flowing through fewer transmission lines. System operation must stay inside the load level for the nose of Curve B. If another contingency occurs, then the next worst contingency is considered along Curve C. The WAMPACS must increase local generation to reduce the power being transmitted from the remote generators to reduce losses and increase voltage at the load center to within the safe zone, to avoid going over the nose of Curve C.

c) Optimal power-flow control (OPFC)

Optimal power-flow control (OPFC) adjusts localized resources such as transformer tap changers and reactive-power compensation devices in response to the dynamic system rating (DSR) confirmed by DLR and DPR acting together. OPFC enhances voltage stability limits and increases power flow.

A detailed list of power-flow control (PFC) equipment is the following:

- Load-tap-changing transformers
- Shunt capacitors
- Series capacitors
- Shunt reactors
- Static VAr compensators (SVCs)
- Static synchronous condensers (SSCs)
- Phase-angle regulating transformers
- Static synchronous compensator (STATCOM), static synchronous series compensators (SSSC) and other flexible AC transmission system (FACTS) devices available on the system and on neighboring interconnected systems

Shunt-connected devices change the transmitting and receiving voltages V_1 and V_2 in the numerator of (1) and (2). These devices are SVCs, SCC (STATCOMs), synchronous condensers SSCs, shunt caps and series-connected, load-tap-changing transformers.

Series-connected devices change the impedance jX in the denominator of (1) and (2). These devices are fixed, series-compensation capacitors and static synchronous series compensators (SSSC).

Phase-shifting transformers control the phase angle δ in (1) and (2).

IV. DSR calculations and effects

The DSR calculations begin with three main parts: determining the thermal rating, angular stability, and voltage stability, as shown in Fig. 5.

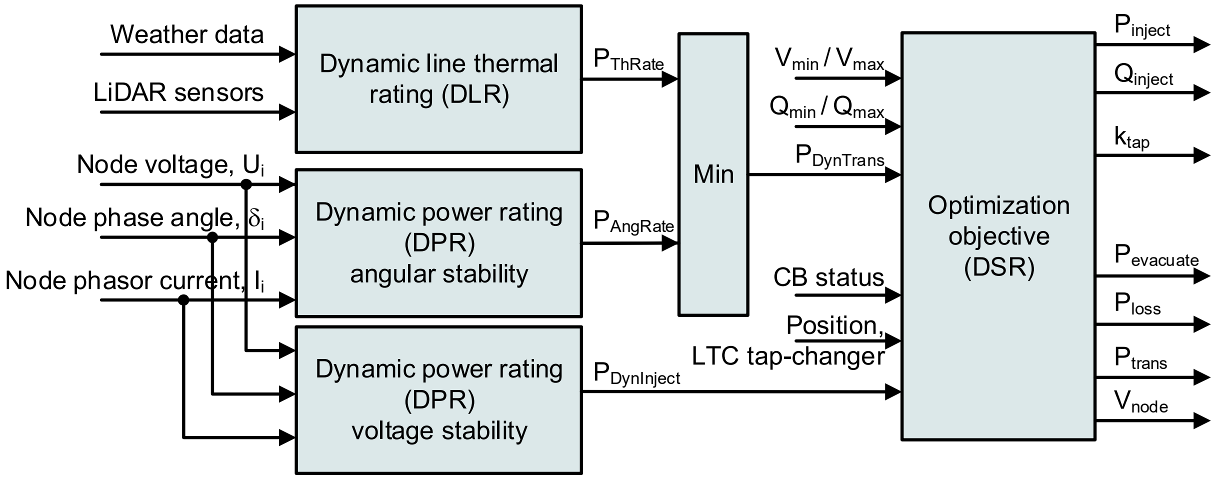

Fig. 5. DSR quantities and calculations

The power thermal and angular rates create a dynamic power setpoint for transmission. This quantity and the dynamic power voltage-stability injection feeds an optimization engine for the dynamic system rating DSR. The optimization engine has voltage and VAr setpoints plus inputs from the circuit-breaker and tap-changer statuses. The outputs from the optimization engine produce power and VAr injections, tap position, power evacuation, power loss, power transmission and voltage-node outputs.

d) DSR better than steady-state estimation (SSE)

With the penetration of utility-scale renewables, power flows on given lines and power corridors might encroach on any of the system-rating constraints. Traditionally, power-transfer rating was performed by the energy-management system (EMS) using steady-state estimation (SSE). Drawbacks of estimation are these:

- Utilities create margin to account for measurement and modeling errors
- SSE uses transducers and line models to calculate bus angles
- Not real time

Traditional WAMPACS (remedial action systems—RAS, system integrity protection schemes—SIPS and special protection schemes—SPS) use synchrophasors to detect instability (out-of-step, voltage collapse, frequency excursions, etc.) [11]. DSR goes further in that it incorporates the synchrophasor information for real-time, transient-stability analysis to provide immediate, power-transfer-limit information. Traditional RAS, SIPS and SPS are reactive to stability issues. DSR enables a proactive WAMPACS to safeguard stable operation. It is real-time calculation versus state estimation.

V. Implementing a DSR WAMPACS

A DSR WAMPACS is constructed with one of many DLR solutions. This new system adds DPR voltage-stability and angular-stability computation to existing DLR thermal solutions, as shown by the transient margin in Fig. 6, to increase the line rating. AAR (ambient adjusted rating) and AAR+ are computational models that do not use sensor inputs.

DSR is agnostic to the DLR source. The DSR can be DPR partnered with LiDAR (light detection and ranging) sensors and modeling [12]. Other DLR systems can be line-contact sensors [13], or software only [14].

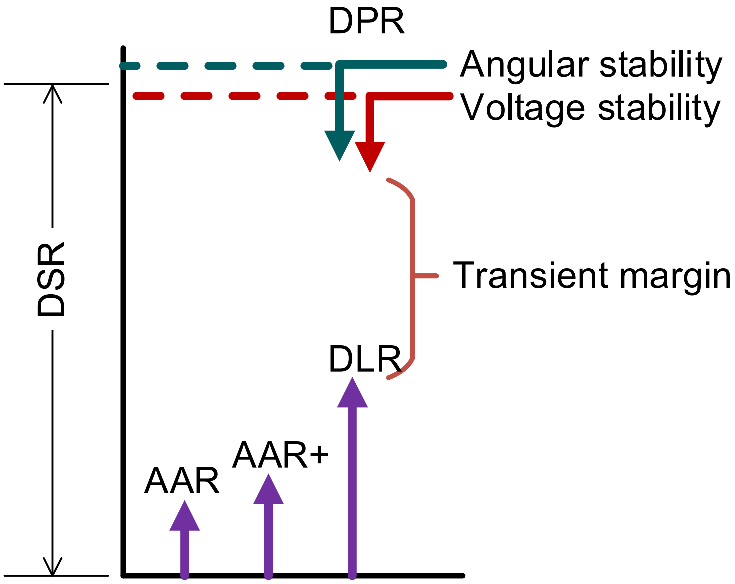

Fig. 6. DPR angular- and voltage-stability increases power flow over DLR alone

A typical transmission-line corridor equipped with a DSR WAMPACS is shown in Fig. 7. Both line sensors and phasor-measurement units (PMUs) contribute to this DSR solution.

a) LiDAR-sensors DLR

LiDAR line sensors (orange triangles in Fig. 7) are installed at the beginning, middle and end of the lines. These sensors, shown in Fig. 8, report to a DLR real-time computer running the DLR thermal-model solution through cellular LTE communication. This communications network is readily available even in remote areas.

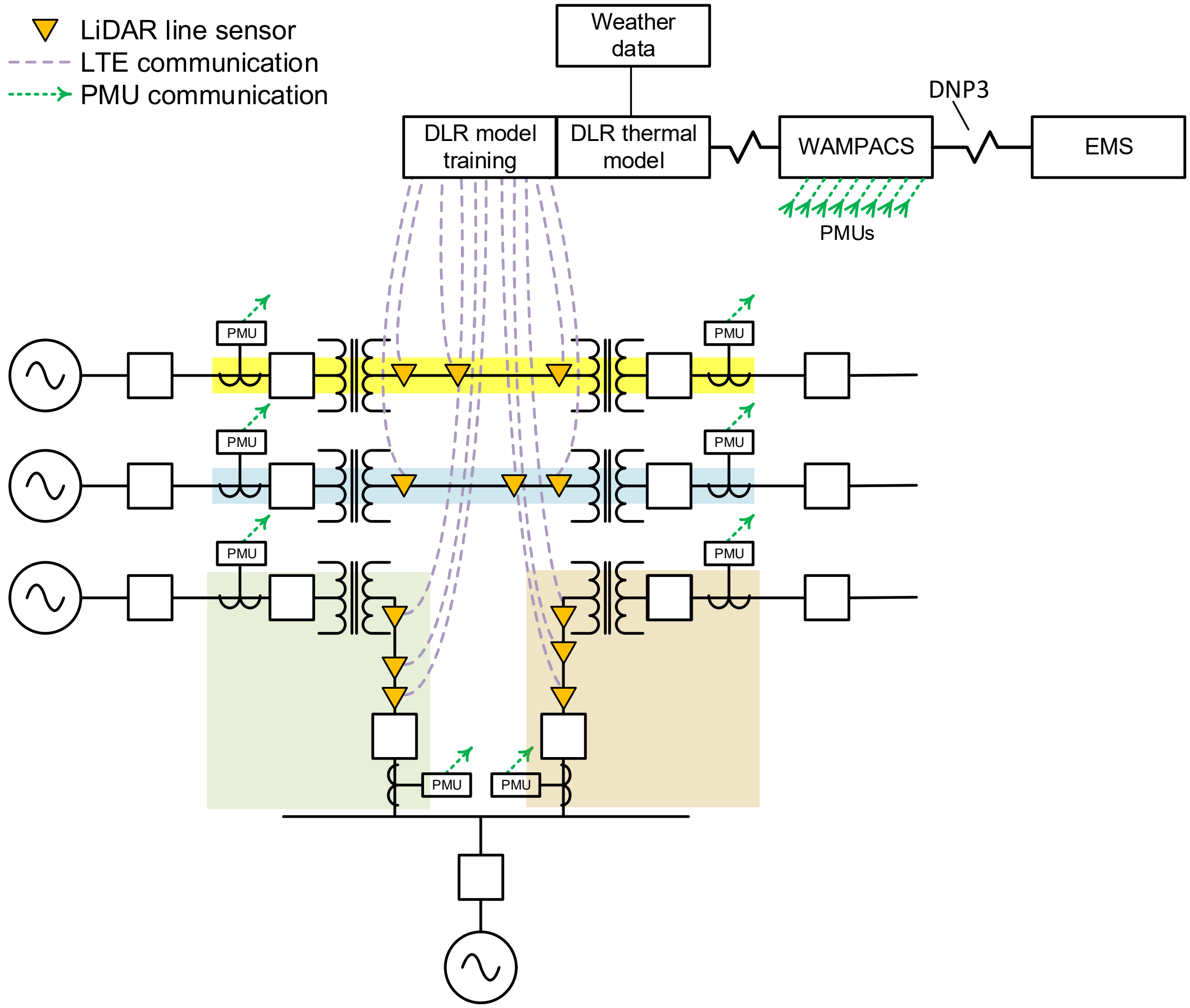

Fig. 7. DSR WAMPACS sensor placement, PMUs, and communication

Fig. 8. LiDAR sensor mounted on transmission-tower strut

LiDAR measurements capture power-line sag and sway under different weather conditions, and electromagnetic readings assess line tensile strength. The non-contact line sensors eliminate the need for expensive installation outages, specialized equipment, and at-risk work for line crews. LiDAR technology monitors all phases of power, even bundled conductors, at any voltage, with just one sensor (no need for a dedicated sensor for each conductor of the transmission line). The sensor power is from a solar panel (mounted below) feeding a long-lasting, lithium-iron-phosphate (LiFePO4) battery installed in a stainless-steel enclosure mounted below the sensor.

b) Phasor-measurement units (PMUs)

In addition to sensors, phasor-measurement units (PMUs) shown in Fig. 7 send data about line voltage and current to the real-time, stability and optimization, WAMPACS, real-time controller. The PMU functionality can come from existing protection relays (add the PMU option, if necessary) for an economical solution, or can be newly installed devices. The real-time, DSR controller acts as the phasor-data concentrator. The transmission network has existing fiber-optic/microwave-radio communication at the substations, so gathering the PMU data is straightforward. The WAMPACS DSR controller sends commands to the EMS for power-system control actions (in this example through the DNP3 link in Fig. 7).

c) DSR WAMPACS supplements existing substation equipment

The system “bolts over” the lines and buses under evaluation and is very effective in a zone with large renewable penetration. Changes to the installed substation equipment are not required. There is no need to interface with a utility geographical information system (GIS); the DSR WAMPACS employs separate measurement and calculation to arrive at rating values.

VI. What DSR provides to operators and to the EMS

DSR outputs present valuable data to power-system operators and to the EMS:

- Information on power-transfer limits per line in a power corridor
- DLR (thermal) and DPR (angular and voltage stability) for each line
- Worst-constraint limit
- Operator suggestions for control of power-flow elements to optimize energy transfer, changing the operating schedule (redispatch)
- Commands for operator confirmation (e.g., L1 West Terminal: raise LTC two taps)
- Direct control of power-flow elements where fast response is needed (e.g., Bus 3: SVC to 3MVAr)

VII. Benefits of DSR

DSR solves congestion and curtailment problems by enabling more power transfer across a line. It evacuates more power from energy sources, both conventional and renewable. DSR fosters use of the least-cost marginal power from renewable sources. Other benefits of installing a DSR WAMPACS are the following:

- Accelerates interconnection of renewable assets—expedites the queue of generation and storage waiting to be connected
- Reduces congestion and curtailment—manages congestion costs to consumers and curtailment management cost to developers

- Enhances grid resilience—provides thermal, angular and voltage stability assessment that enables additional, real-time, capacity throughput
- Increases situational awareness—ensures end-to-end lines and switching elements are within safe operating limits with real-time alerts on threats to grid reliability and public safety
- Supports asset health insight—increases data which improves asset management of lines and switching elements, providing predictive and prescriptive solutions

VIII. Simulation results

Laboratory simulations have verified increased power flow with DSR. Researchers modeled multiple weather conditions and line parameters. Different IBR resources from solar and wind generation contributed to the line power-flow simulations. These simulations showed significant increases in line capacity.

IX. Conclusions

The traditional method of WAMPACS adjustments to transmission-system power flow was reactive, using fixed ratings and state estimation. Now, powerful, distributed, computing platforms are available that acquire synchrophasor data from relays and dedicated PMUs to determine the line dynamic power rating (DPR) angular and voltage stability, on top of the dynamic line rating (DLR) thermal data. Thus, DSR provides a complete, dynamic system rating for given lines and power corridors.

This proactive WAMPACS, as a grid-enhancing technology (GET), handles the increasing penetration of inverter-based resources (IBRs), which produce variable voltage and current outputs and reduce power-system inertia. This system provides precise, transient-stability, power-flow limit determination, with contingency analysis. Thus, maximum safe power flow occurs on lines and load buses in the PMU-monitored area.

The DSR WAMPACS addresses the negative aspects of grid congestion and curtailment. It provides real-time calculation and contingency analysis to redirect and redispatch power flow, to improve transient stability.

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