Operational Integration of Dynamic Line Rating Using IEC 60870-5-104 and CIM/CGMES

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***Abstract*—Dynamic Line Rating (DLR) can alleviate thermal limitations in electrical grids by adapting line ampacity to actual and forecasted weather instead of conservative static assumptions. In practice, many DLR projects remain pilots, mainly because integration into existing Control Center systems and workflows is difficult. This paper focuses on how to bring conservative, span-aware DLR into real operation using interfaces and data models that System Operators already use.**

We present a software-based, standards-compliant pipeline. Span ampacities are computed from hyper-local weather forecasts using IEEE 738 and probabilistic methods, then aggregated to line-level "Secure DLR" based on a 98% confidence level. Real-time Secure DLR ratings are sent as analogs over IEC 60870-5-104 to SCADA (Supervisory Control and Data Acquisition)/EMS (Energy Management System) or DMS (Distribution Management System), and the same ratings are represented as ampere-based objects in CIM (The Common Information Model)/CGMES (Common Grid Model Exchange Specification) based Operational Planning Grid Models. The solution reuses existing SCADA and Planning Tool interfaces, provides clear fallback to AAR and Seasonal Ratings, and avoids large sensor rollouts.

Deployment at the Estonian 110/330 kV Transmission Grid Operator validates the approach feasibility. Results indicate that a standards-based integration path can move DLR from pilots into day-to-day control center operation with acceptable risk and limited changes in existing tools.

***Index Terms*—Dynamic Line Rating, IEC104, CIM, CMGES, Line Ratings**

I. Introduction

Transmission and distribution grids are changing fast due to renewable integration, electrification and new large loads, while permitting and physical grid reinforcement still move slowly. One practical way to reduce this gap is to use Dynamic Line Rating (DLR) to extract more capacity from existing overhead lines by relaxing conservative static assumptions when weather conditions are favourable.

The fundamentals of thermal line rating and the dependence of convective cooling on weather are well established, starting from the classical work of House and Tuttle on ACSR ampacity [1], the IEEE Std 738 family [2] and the CIGRÉ Technical Brochures 207 and 601 on thermal behaviour and thermal rating calculations of overhead lines [3], [4]. Most published work on Dynamic Line Rating focuses on forecasting methods and pilot-scale demonstrations such as[5], [6], [7], [8], [9]. Recent papers compare different DLR forecasting approaches and quantify uncertainty in ampacity predictions, typically with day-ahead or hour-ahead horizons and under favourable weather conditions, DLR can increase available transfer capacity by roughly 20–30% compared to conservative static ratings on the same circuits [10], [11], [12], [13].

However, these studies largely stop at the level of rating calculation, forecasting performance and isolated use cases. They rarely show DLR limits being fed systematically into the existing operational planning chain (for example capacity-calculation models, contingency analysis or market coupling workflows). In most cases, DLR remains a parallel pilot tool rather than a fully integrated element of day-to-day operational planning.

The main problem is usually not in the DLR physics, but in integration into existing IT and operational environments. Control Centres use systems with long lifecycles, strict cyber-security requirements and a conservative change culture. SCADA (Supervisory Control and Data Acquisition), EMS (Energy Management System), DMS (Distribution Management System) and market tools have evolved on a different track compared with modern IT, so it is difficult to introduce new software based on contemporary web APIs (Application Programming Interface) and to connect it in a way that is accepted by operators and vendors.

In practice, Control Center systems already support a small set of sector-specific interfaces "out of the box". In Europe, analog telemetry and status information typically enter SCADA through IEC 60870-5-104 [14], [15], while network models and planning data are exchanged using CIM (The Common Information Model)/CGMES (Common Grid Model Exchange Specification) profiles as required by European grid codes for capacity calculation and operational security analyses [16], [17], [18], [19]. Operators and vendors know these standards well and have established engineering processes around them. This is a strong lever for DLR deployment, because it allows us to introduce dynamic ratings via channels and data models that are already trusted in conservative SCADA, EMS and DMS environments.

In this paper we explore how to integrate DLR into existing IT systems and operational workflows by reusing these Energy Sector specific communication channels and data formats based on Estonian example. We focus on an architecture where a DLR application produces probabilistic, span-aware line ratings based on hyper-local weather forecasts and IEEE 738 calculations, and then exposes these ratings in two ways: (i) as analog measurements via IEC 60870-5-104 towards SCADA/EMS or DMS, and (ii) as thermal limits in CIM/CGMES grid models used for Operational Planning and

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Planning Tools. The goal is to enable higher utilization of existing grid hardware while keeping explicit safety margins and clear fallbacks.

The contributions of this paper are:

- a standards-based architecture for ingesting probabilistic DLR into SCADA systems via IEC 60870-5-104, implemented as a virtual RTU that sends DLR ratings as conventional analog telemetry;
- a process description of updating Line Current Limits in CIM/CGMES based Gird Models used for Operational Planning, so that dynamic line ratings can be used consistently in contingency and capacity calculations for all operational planning time-horizons;

II. Dynamic Line Ratings

In this section we describe how Dynamic Line Ratings (DLR) are calculated and transformed into operationally usable limits for Control Center systems. The focus is on implementation: we convert probabilistic, span-based DLR into per-line, time-horizon dependent "Secure DLR" values that can be consumed by SCADA/EMS or DMS and Planning Tools. The DLR calculation is based on our previous work on hyper-local and is only summarized here.

A. Hyper-local DLR Calculation

The DLR engine follows the process in [20] using probabilistic rating values with confidence bounds. For each time step and span it gathers conductor parameters, allowed span temperatures, terrain and numerical weather prediction (NWP) data, runs a hyper-local weather model and calculates span ampacity with the IEEE 738 heat balance. The machine learning model gives predictive distributions for the main weather drivers (wind speed, wind direction, ambient temperature and solar irradiance). Details of the model, training data and validation are given in [20]. Surface absorptivity and emissivity are typically 0.9, but can be adjusted based on conductors. The maximum operating temperature is set by the System Operator and for ACSR is usually 45, 60, 75 or 80 °C, with higher values possible for AAAC and ACCC.

B. Seasonal Ratings and Ambient Adjusted Rating

In addition to DLR we keep traditional Static Ratings as baseline and fallback. For Static Rating we use Seasonal Ratings, where the year is split into time blocks with fixed weather parameters. For example, from 1 January to 1 March we might use ambient temperature 0 °C, wind speed 0.61 m/s, wind attack angle 90 degrees and solar irradiance 400 W/m^2, which are then used in IEEE 738 to get a constant ampacity. Ambient Adjusted Rating (AAR) is calculated in a similar way, we use wind parameters from the Seasonal configuration, but compute clear-sky solar irradiance and predict temperature.

C. Secure DLR and Aggregation to Line Level

To use DLR in conservative SCADA, EMS or DMS environments we derive a single "Secure DLR" value per time step, that behaves similarly to static ratings in terms of risk. For each span and time step we select a lower confidence bound on the DLR distribution. Here we use a 98% confidence level: the chosen DLR value has about 2% probability that true ampacity is lower. This gives a rating that is safe in 98% of situations, on the assumption that confidence intervals are respected, roughly comparable to well-designed Seasonal Ratings.

After computing Secure DLR for each span, we aggregate to line level by taking the minimum:

$$I_{\text{SecureDLR,line}}(t) = \min_{s \in \text{spans(line)}} I_{\text{SecureDLR,span}}(s,t), \qquad (1)$$

so the most limiting span sets the line rating. The computation gives a DLR Forecast that is a time-series of foreacasted DLR [CI 50% ... CI 99%], AAR and SR per Line, up to ten days ahead.

D. Fallback Between DLR, AAR and Seasonal Ratings

Because DLR depends on external data (weather, terrain) and a more complex chain, a clear fallback logic is needed. In our implementation it is applied per line and time step:

- use Secure DLR if a value exists and all quality checks pass (inputs not missing, model run on time);
- otherwise use AAR if available;
- otherwise use Seasonal Rating.

This logic is applied before sending ratings over IEC 60870-5-104, so the Control Center always receives a single active thermal limit per line and per time step, with the origin (DLR, AAR or Seasonal) known on the DLR side.

We also apply a small set of generic safeguards:

- **Fail-safe floor:** $\text{DLR}_{op} = \max(\text{DLR}_{secure}, \text{SR})$.
- **Bounded look-ahead:** align time-horizons with dispatch intervals (e.g., 60 min or 15 min) for stability.
- **Rate limits:** cap update frequency according to SCADA capabilities.
- **Alarms:** configure SCADA/EMS or DMS to use dynamic limits for alarms instead of static constants.
- **Audit:** log IOA, value, time period, and forecast version/id for traceability.

E. Preparation of Ratings for Control Center Integration

After calculating Secure DLR, AAR and Seasonal Ratings at line level, each rating value is stored together with metadata that identifies the line, rating type, time period in the DLR Application. The Ratings can be retrieved by using the DLR Application REST API shown in Fig. 3.

F. Selecting Relevant time periods

In Operations and in Operational planning there are reoccurring processes that are defined by relative time e.g. time horizons. The processes usually are not looking at constant time window from current moment, but rather the reference point in time is current hour start or current day start. For Operations common time-horizons are current hour (H-0) and next hour (H-1), counting from the start of the hour. For Operational Planning time horizons vary from year ahead (Y-1) to intraday (D-0), but most relevant from DLR point of view are D-0, D-1

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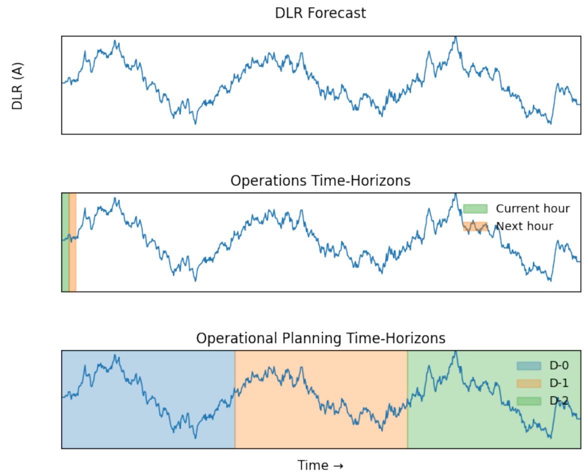

Fig. 1. Conceptual diagram of DLR Time-Horizons for different use-cases.

and D-2 (Fig 1). While AAR is used for W-1 processes and for M-1 and Y-1 processes the Seasonal Ratings are used.

The DLR application converts relative time definitions seen in Listing 1 and Algorithm 1 into concrete UTC time periods ("current hour" or "next day"). In practice it means, for each process the relevant time period is selected from the latest DLR forecast available at the start of the given process using the following steps:

Algorithm 1 Conversion of Relative Time Period to Concrete Time Window

1: **Input:** `reference_dynamic`, `start_delta`, `end_delta`, `timezone`
2: Get current time in configured timezone: `now = datetime.now(timezone)`
3: Resolve dynamic reference to concrete timestamp: `reference_concrete = reference_times[reference_dynamic](now)`
4: Compute start of interval in UTC
5: Compute end of interval in UTC
6: **Output:** `start`, `end` (both in UTC)

III. SCADA Integration using IEC 60870-5-104

A. Mapping of Identifiers

For SCADA/EMS integration via IEC 60870-5-104, this metadata is mapped to analog information objects with specific information object addresses (IOAs) (See Listing 1).

B. System Architecture and Virtual RTU

The system has three main building blocks:

- the DLR Application calculates span-based probabilistic ampacity and aggregates it to line-level Secure DLR, AAR and Seasonal Ratings;
- a IEC 104 Module of the application, that prepares these ratings for Control Center use, applies fallback logic and exposes the data via standard interfaces;
- Control Centre system SCADA/EMS or DMS that ingest the ratings via IEC 60870-5-104.

The SCADA system establishes connection to the DLR application as if it were Remote Terminal Unit (RTU). DLR Application has a IEC 104 connection Module that implements IEC 60870-5-104 and publishes analog measurements in the same way as conventional RTUs (Fig 3). Each Secure DLR value that we expose to the Control Center is mapped to an IEC 60870-5-104 information object; we use the standard `M_ME_NC_1` (short floating point) type to carry the ampacity in amperes for the corresponding line and configured time-horizon.

C. Point Configuration, Mapping and Update Logic

The mapping from line-level ratings to IEC 60870-5-104 points is defined in a configuration file. An excerpt is shown in Listing 1.

Listing 1. IEC 104 point config (excerpt from `point_config.json`).

```
[
  {
    "name": "Test Line 1 - current hour",
    "external_id": "06847e9c-...",
    "io_address": 11,
    "type": "M_ME_NC_1",
    "attribute": "ratings.dlr.98",
    "reference_time_enum": "currentHourStart",
    "start_delta": "PT0H",
    "end_delta": "PT1H",
    "timezone": "Europe/Brussels"
  }
]
```

At start-up the DLR application reads the configuration, subscribes to the corresponding line-level ratings and creates the IEC 60870-5-104 information objects. The publisher loop then periodically fetches the latest ratings, selects the correct time period data form DLR Forecast and sends updated values to the SCADA system, as shown in Algorithm 2.

Algorithm 2 IEC 104 Publisher Loop

1: Fetch latest Ratings Forecast per point in configuration (Listing 1)
2: Select data from DLR Forecast for configured time horizon
3: Aggregate to a Secure DLR value per line (e.g., concrete time period minimum)
4: Enforce fail-safe floor and fallback logic
5: Transmit values over IEC 60870-5-104 to SCADA
6: Wait for configured interval (e.g., 30 s) and repeat

For Operations it is relevant to monitor the system, if it is within operational limits and is following the Operational Plan, and have a good understating of upcoming changes (both magnitude and direction). Thus for Operations in SCADA/EMS or DMS there are two telemetry points defined per line, one for current hour (H-0) and one for next hour (H-1).

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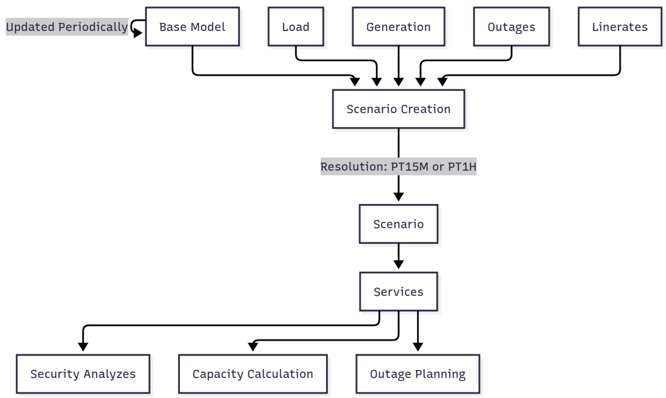

Fig. 2. Conceptual diagram of Scenario Creation

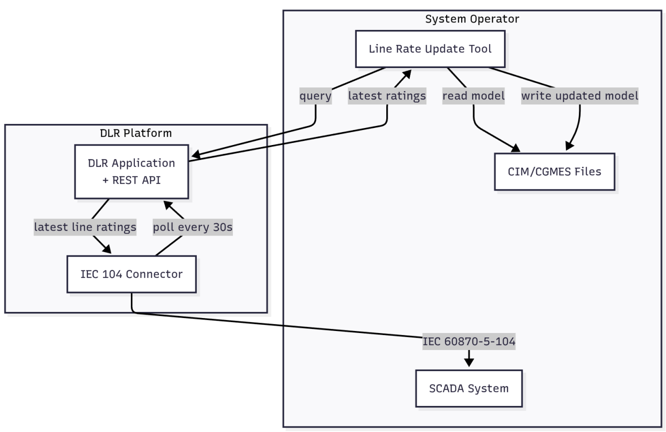

Fig. 3. Conceptual Architecture overview: DLR Platform integrations with System Operator. DLR application as virtual RTU over IEC 60870-5-104 with SCADA, and CIM/CGMES format planning models with updated `cim:CurrentLimit` objects to operational planning tools.

IV. Planning-Tools Integration using CIM/CGMES

For planning tools, the interface is CIM/CGMES based models, we implement into Case Creation process an additional line rate update process (Fig 2).

A. Mapping of identifiers

For planning tools using CIM/CGMES, the line mRID is used to map the forecast to a Line in the model. The DLR Application allows to define external identifiers, in our case corresponding cim:ACLineSegments have been stored in the application, enabling to retrieve the data via API using identifiers directly present in the CIM/CGMES based Grid Model. Equipment not matching is logged and reported.

B. Connection Setup and Data Formats

Connection with DLR Application is made via HTTP/REST API, either on-site or on-cloud, that returns JSON payloads, containing DLR, AAR Forecast and SR Data. Grid Model is available in standardized zipped XML/RDF format (Fig 3).

C. CIM/CGMES Network Model Updates

For operational planning and planning tools that use CIM/CGMES, we export the same ratings as thermal limits in the network models. We follow the standard CGMES approach using `cim:CurrentLimit` objects for each line with dynamic ratings [18], [19]. In CGMES 2.4 the Limits are contained in EQ profile. Limits are usually mapped to cim:ACLineSegment via cim:Terminals (Fig 4. CGMES has constrained CIM on the allowed limits and types, we are updating Permanently Allowed Temperature Limits (PATL).

The workflow for updating CIM/CGMES models is shown in Algorithm 3 and relevant CIM data-model Classes and associations are shown on Fig 4.

Algorithm 3 Workflow for Updating Operational Limits

1. Load CIM/CGMES-based Network Model
2. Find all limit objects inheriting from `cim:OperationalLimit`
3. De-normalise limits on `cim:OperationalLimitSet`
4. Filter for `cim:OperationalLimitType` of type PATL
5. For each `cim:ACLineSegment`, get Secure DLR from the DLR application
6. Set `cim:CurrentLimit.value` where Secure DLR is available
7. Set limit object type to `cim:CurrentLimit` and clean other attributes
8. Export updated CIM/CGMES Network Model

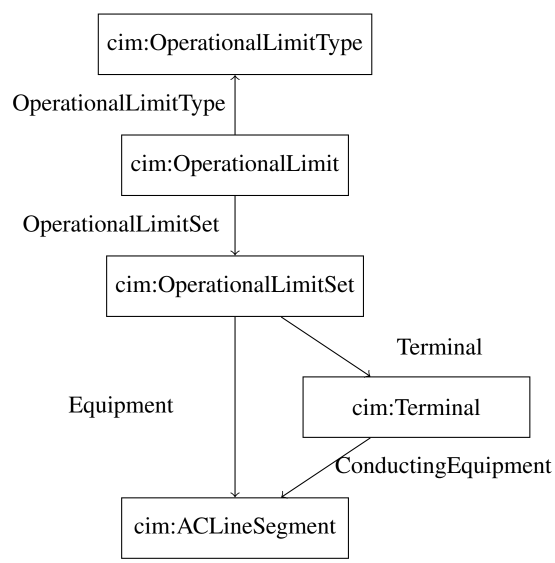

Fig. 4. CIM Classes and their Relations for Operational Limits extraction.

Figure 5 provides an example, based on ENTSO-E test model ”Real Grid” [21], how logic described in Algorithm 3 updates the Current Limit in CIM/CGMES format Operational Planning Grid Model. The XML structure remains the same except for the change from 681 to 833 in the `<cim:CurrentLimit.value>` element, as shown below:

```
<cim:CurrentLimit rdf:ID="_426798065_ACLS_CL00">
   -- <cim:CurrentLimit.value>681.000000</cim:CurrentLimit.
        value>
   ++ <cim:CurrentLimit.value>833.0</cim:CurrentLimit.value>
   <cim:OperationalLimit.OperationalLimitSet rdf:resource="#
        _426798065_ACLS_T0_OLS"/>
   <cim:OperationalLimit.OperationalLimitType rdf:resource="
        #_PATL-1_OLT"/>
</cim:CurrentLimit>
```

Fig. 5. RDF/XML Diff Highlighting Current Limit Adjustment in CIM Model. Removed lines in red (–), added lines in green (++).

V. Results

In the Estonian implementation, our approach allowed DLR to be brought into day-to-day Control Centre operation without changes to core EMS or planning tools. DLR is incorporated into existing processes as Secure DLR based on a 98% confidence level.

Operators see familiar ampacity values and quality information in EMS and can take informed actions on more accurate data regarding the lines thermal capability. (e.g. Implement timely remedial actions or use more cross-border capacity for frequency and balance reserves)

Operational Planning processes uses consistent limits for D-0 ... W-1 studies, after the Study Cases for given time-horizon are created, they are used in one or more Operational Planning processes (e.g. Outage Planning, Security Analyzes, Capacity Calculations) but also shared (in accordance with EU grid codes) with other TSO-s and RCC-s. Main benefits are yet to be quantified, but more accurate data in Planning will bring more secure operations, lower energy prices and more efficient grid maintenance.

VI. Conclusions and Future Work

We presented a minimal and robust integration path for DLR based on a software DLR system that covers the whole network and provides multi-day forecasts. Real-time ratings are sent as analogs over IEC 60870-5-104 towards SCADA/EMS or DMS, and the same ampere-based limits are represented as `cim:CurrentLimit` objects in CIM/CGMES Operational Planning Models. This pattern avoids sensor rollout projects, reuses existing interfaces and tools, and provides clear fallback to AAR and Seasonal Ratings.

Planned enhancements include moving from 1 h to 15 min time resolution, adding explicit Emergency Ratings alongside normal limits, and exposing data quality and origin via IEC 60870-5-104 flagging to make the behaviour more transparent for operators and downstream tools.

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