KRISHANU DAS
G24AI2013
FDS ASSIGNMENT - 1

2. Dynamic Load Balancing for a Smart Grid

Objective

The objective of this project was to simulate a scalable smart grid system that dynamically balances incoming Electric Vehicle (EV) charging requests across multiple substations, ensuring optimal utilization and preventing overload. The system includes a full observability stack for real-time monitoring using industry-standard tools.

System Architecture

The system is implemented using a microservices-based architecture in Python, with all services containerized and orchestrated using Docker Compose. The key components include:

1. Substation Service

- Simulates an EV charging substation.
- Maintains and exposes a live metric (`substation_current_load`) representing the number of active charging sessions.
- Metrics are formatted for Prometheus scraping and exposed via a `/metrics` endpoint.
- Handles `POST /charge` requests with simulated delays and concurrent load tracking.

Glimpse of the logs for substation service

```
load_balancer-1   | 2025-06-23 21:27:51,449 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation1:5002
substation1       | 2025-06-23 21:27:51,451 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:51] "GET /metrics HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:51,452 [DEBUG] [LOAD_BALANCER]
http://substation1:5002 "GET /metrics HTTP/1.1" 200 116
load_balancer-1   | 2025-06-23 21:27:51,453 [DEBUG] [LOAD_BALANCER]
Substation http://substation1:5002 has load 0.0
load_balancer-1   | 2025-06-23 21:27:51,454 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation2:5002
substation2       | 2025-06-23 21:27:51,457 [INFO] [SUBSTATION] 172.23.0.7
```

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- - [23/Jun/2025 21:27:51] "GET /metrics HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:51,457 [DEBUG] [LOAD_BALANCER]
http://substation2:5002 "GET /metrics HTTP/1.1" 200 116
load_balancer-1   | 2025-06-23 21:27:51,458 [DEBUG] [LOAD_BALANCER]
Substation http://substation2:5002 has load 2.0
load_balancer-1   | 2025-06-23 21:27:51,458 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation3:5002
substation3       | 2025-06-23 21:27:51,459 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:51] "GET /metrics HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:51,460 [DEBUG] [LOAD_BALANCER]
http://substation3:5002 "GET /metrics HTTP/1.1" 200 116
load_balancer-1   | 2025-06-23 21:27:51,460 [DEBUG] [LOAD_BALANCER]
Substation http://substation3:5002 has load 1.0
load_balancer-1   | 2025-06-23 21:27:51,460 [INFO] [LOAD_BALANCER] Routing
vehicle EV-42 to http://substation1:5002
load_balancer-1   | 2025-06-23 21:27:51,461 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation1:5002
substation1       | 2025-06-23 21:27:51,462 [INFO] [SUBSTATION] Charging
vehicle EV-42
charge_request-1  | 2025-06-23 21:27:51,944 [INFO] [CHARGE_SERVICE]
Received charge request from vehicle EV-43
charge_request-1  | 2025-06-23 21:27:51,946 [DEBUG] [CHARGE_SERVICE]
Starting new HTTP connection (1): load_balancer:5001
load_balancer-1   | 2025-06-23 21:27:51,950 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation1:5002
substation1       | 2025-06-23 21:27:51,952 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:51] "GET /metrics HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:51,955 [DEBUG] [LOAD_BALANCER]
http://substation1:5002 "GET /metrics HTTP/1.1" 200 116
load_balancer-1   | 2025-06-23 21:27:51,956 [DEBUG] [LOAD_BALANCER]
Substation http://substation1:5002 has load 1.0
load_balancer-1   | 2025-06-23 21:27:51,957 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation2:5002
substation2       | 2025-06-23 21:27:51,959 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:51] "GET /metrics HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:51,960 [DEBUG] [LOAD_BALANCER]
http://substation2:5002 "GET /metrics HTTP/1.1" 200 116
load_balancer-1   | 2025-06-23 21:27:51,961 [DEBUG] [LOAD_BALANCER]
Substation http://substation2:5002 has load 2.0
load_balancer-1   | 2025-06-23 21:27:51,962 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation3:5002
substation3       | 2025-06-23 21:27:51,963 [INFO] [SUBSTATION] 172.23.0.7
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Substation http://substation3:5002 has load 1.0
load_balancer-1  | 2025-06-23 21:27:51,964 [INFO] [LOAD_BALANCER] Routing
vehicle EV-43 to http://substation1:5002
substation3     | 2025-06-23 21:27:51,964 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:51] "POST /charge HTTP/1.1" 200 -
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substation1     | 2025-06-23 21:27:51,967 [INFO] [SUBSTATION] Charging
vehicle EV-43
charge_request-1 | 2025-06-23 21:27:51,967 [INFO] [CHARGE_SERVICE]
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charge_request-1 | 2025-06-23 21:27:52,449 [INFO] [CHARGE_SERVICE]
Received charge request from vehicle EV-44
charge_request-1 | 2025-06-23 21:27:52,451 [DEBUG] [CHARGE_SERVICE]
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Substation http://substation3:5002 has load 0.0
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vehicle EV-44 to http://substation3:5002
load_balancer-1   | 2025-06-23 21:27:52,471 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation3:5002
substation3       | 2025-06-23 21:27:52,471 [INFO] [SUBSTATION] Charging
vehicle EV-44
charge_request-1  | 2025-06-23 21:27:52,950 [INFO] [CHARGE_SERVICE]
Received charge request from vehicle EV-45
charge_request-1  | 2025-06-23 21:27:52,951 [DEBUG] [CHARGE_SERVICE]
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charge_request-1  | 2025-06-23 21:27:53,456 [INFO] [CHARGE_SERVICE]
Received charge request from vehicle EV-46
charge_request-1  | 2025-06-23 21:27:53,458 [DEBUG] [CHARGE_SERVICE]
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Substation http://substation1:5002 has load 1.0
load_balancer-1   | 2025-06-23 21:27:53,470 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation2:5002
charge_request-1  | 2025-06-23 21:27:53,472 [INFO] [CHARGE_SERVICE]
192.168.65.1 - - [23/Jun/2025 21:27:53] "POST /charge HTTP/1.1" 200 -
substation2       | 2025-06-23 21:27:53,473 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:53] "GET /metrics HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:53,474 [DEBUG] [LOAD_BALANCER]
http://substation2:5002 "GET /metrics HTTP/1.1" 200 116
load_balancer-1   | 2025-06-23 21:27:53,474 [DEBUG] [LOAD_BALANCER]
Substation http://substation2:5002 has load 1.0
load_balancer-1   | 2025-06-23 21:27:53,475 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation3:5002
substation3       | 2025-06-23 21:27:53,476 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:53] "GET /metrics HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:53,477 [DEBUG] [LOAD_BALANCER]
http://substation3:5002 "GET /metrics HTTP/1.1" 200 116
load_balancer-1   | 2025-06-23 21:27:53,477 [DEBUG] [LOAD_BALANCER]
Substation http://substation3:5002 has load 1.0
load_balancer-1   | 2025-06-23 21:27:53,477 [INFO] [LOAD_BALANCER] Routing
vehicle EV-46 to http://substation1:5002
load_balancer-1   | 2025-06-23 21:27:53,477 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation1:5002
substation1       | 2025-06-23 21:27:53,479 [INFO] [SUBSTATION] Charging
vehicle EV-46
charge_request-1  | 2025-06-23 21:27:53,959 [INFO] [CHARGE_SERVICE]
Received charge request from vehicle EV-47
charge_request-1  | 2025-06-23 21:27:53,960 [DEBUG] [CHARGE_SERVICE]
Starting new HTTP connection (1): load_balancer:5001
load_balancer-1   | 2025-06-23 21:27:53,965 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation1:5002
substation1       | 2025-06-23 21:27:53,968 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:53] "GET /metrics HTTP/1.1" 200 -
substation1       | 2025-06-23 21:27:53,968 [INFO] [SUBSTATION] 172.23.0.7
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http://substation1:5002 "POST /charge HTTP/1.1" 200 31
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Response from http://substation1:5002: 200 {'status': 'Charging complete'}
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172.23.0.8 - - [23/Jun/2025 21:27:53] "POST /route HTTP/1.1" 200 -
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Substation http://substation1:5002 has load 2.0
charge_request-1 | 2025-06-23 21:27:53,972 [DEBUG] [CHARGE_SERVICE]
http://load_balancer:5001 "POST /route HTTP/1.1" 200 69
load_balancer-1   | 2025-06-23 21:27:53,973 [DEBUG] [LOAD_BALANCER]
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charge_request-1 | 2025-06-23 21:27:53,974 [INFO] [CHARGE_SERVICE]
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Starting new HTTP connection (1): substation2:5002
substation2        | 2025-06-23 21:27:53,981 [INFO] [SUBSTATION] Charging
vehicle EV-47
charge_request-1 | 2025-06-23 21:27:54,459 [INFO] [CHARGE_SERVICE]
Received charge request from vehicle EV-48
charge_request-1 | 2025-06-23 21:27:54,460 [DEBUG] [CHARGE_SERVICE]
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substation1       | 2025-06-23 21:27:54,473 [INFO] [SUBSTATION] Charging
vehicle EV-48
substation3       | 2025-06-23 21:27:54,474 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:54] "POST /charge HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:54,474 [DEBUG] [LOAD_BALANCER]
http://substation3:5002 "POST /charge HTTP/1.1" 200 31
load_balancer-1   | 2025-06-23 21:27:54,474 [DEBUG] [LOAD_BALANCER]
Response from http://substation3:5002: 200 {'status': 'Charging complete'}
load_balancer-1   | 2025-06-23 21:27:54,475 [INFO] [LOAD_BALANCER]
172.23.0.8 - - [23/Jun/2025 21:27:54] "POST /route HTTP/1.1" 200 -
charge_request-1  | 2025-06-23 21:27:54,475 [DEBUG] [CHARGE_SERVICE]
http://load_balancer:5001 "POST /route HTTP/1.1" 200 69
charge_request-1  | 2025-06-23 21:27:54,475 [INFO] [CHARGE_SERVICE]
192.168.65.1 - - [23/Jun/2025 21:27:54] "POST /charge HTTP/1.1" 200 -
charge_request-1  | 2025-06-23 21:27:54,966 [INFO] [CHARGE_SERVICE]
Received charge request from vehicle EV-49
charge_request-1  | 2025-06-23 21:27:54,967 [DEBUG] [CHARGE_SERVICE]
Starting new HTTP connection (1): load_balancer:5001
substation2       | 2025-06-23 21:27:54,968 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:54] "POST /charge HTTP/1.1" 200 -
```

```
load_balancer-1   | 2025-06-23 21:27:54,969 [DEBUG] [LOAD_BALANCER]
http://substation2:5002 "POST /charge HTTP/1.1" 200 31
load_balancer-1   | 2025-06-23 21:27:54,969 [DEBUG] [LOAD_BALANCER]
Response from http://substation2:5002: 200 {'status': 'Charging complete'}
load_balancer-1   | 2025-06-23 21:27:54,970 [INFO] [LOAD_BALANCER]
172.23.0.8 - - [23/Jun/2025 21:27:54] "POST /route HTTP/1.1" 200 -
charge_request-1  | 2025-06-23 21:27:54,971 [DEBUG] [CHARGE_SERVICE]
http://load_balancer:5001 "POST /route HTTP/1.1" 200 69
charge_request-1  | 2025-06-23 21:27:54,972 [INFO] [CHARGE_SERVICE]
192.168.65.1 - - [23/Jun/2025 21:27:54] "POST /charge HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:54,972 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation1:5002
substation1       | 2025-06-23 21:27:54,974 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:54] "GET /metrics HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:54,975 [DEBUG] [LOAD_BALANCER]
http://substation1:5002 "GET /metrics HTTP/1.1" 200 116
load_balancer-1   | 2025-06-23 21:27:54,976 [DEBUG] [LOAD_BALANCER]
Substation http://substation1:5002 has load 2.0
load_balancer-1   | 2025-06-23 21:27:54,977 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation2:5002
substation2       | 2025-06-23 21:27:54,978 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:54] "GET /metrics HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:54,978 [DEBUG] [LOAD_BALANCER]
http://substation2:5002 "GET /metrics HTTP/1.1" 200 116
load_balancer-1   | 2025-06-23 21:27:54,979 [DEBUG] [LOAD_BALANCER]
Substation http://substation2:5002 has load 1.0
load_balancer-1   | 2025-06-23 21:27:54,980 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation3:5002
substation3       | 2025-06-23 21:27:54,981 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:54] "GET /metrics HTTP/1.1" 200 -
load_balancer-1   | 2025-06-23 21:27:54,981 [DEBUG] [LOAD_BALANCER]
http://substation3:5002 "GET /metrics HTTP/1.1" 200 116
load_balancer-1   | 2025-06-23 21:27:54,981 [DEBUG] [LOAD_BALANCER]
Substation http://substation3:5002 has load 0.0
load_balancer-1   | 2025-06-23 21:27:54,982 [INFO] [LOAD_BALANCER] Routing
vehicle EV-49 to http://substation3:5002
load_balancer-1   | 2025-06-23 21:27:54,982 [DEBUG] [LOAD_BALANCER]
Starting new HTTP connection (1): substation3:5002
substation3       | 2025-06-23 21:27:54,983 [INFO] [SUBSTATION] Charging
vehicle EV-49
substation1       | 2025-06-23 21:27:55,268 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:27:55] "GET /metrics HTTP/1.1" 200 -
substation2       | 2025-06-23 21:27:55,282 [INFO] [SUBSTATION] 172.23.0.2
```

```
- - [23/Jun/2025 21:27:55] "GET /metrics HTTP/1.1" 200 -
substation1     | 2025-06-23 21:27:55,482 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:55] "POST /charge HTTP/1.1" 200 -
load_balancer-1  | 2025-06-23 21:27:55,484 [DEBUG] [LOAD_BALANCER]
http://substation1:5002 "POST /charge HTTP/1.1" 200 31
load_balancer-1  | 2025-06-23 21:27:55,485 [DEBUG] [LOAD_BALANCER]
Response from http://substation1:5002: 200 {'status': 'Charging complete'}
load_balancer-1  | 2025-06-23 21:27:55,485 [INFO] [LOAD_BALANCER]
172.23.0.8 - - [23/Jun/2025 21:27:55] "POST /route HTTP/1.1" 200 -
charge_request-1 | 2025-06-23 21:27:55,487 [DEBUG] [CHARGE_SERVICE]
http://load_balancer:5001 "POST /route HTTP/1.1" 200 69
charge_request-1 | 2025-06-23 21:27:55,488 [INFO] [CHARGE_SERVICE]
192.168.65.1 - - [23/Jun/2025 21:27:55] "POST /charge HTTP/1.1" 200 -
substation2     | 2025-06-23 21:27:55,988 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:55] "POST /charge HTTP/1.1" 200 -
load_balancer-1  | 2025-06-23 21:27:55,989 [DEBUG] [LOAD_BALANCER]
http://substation2:5002 "POST /charge HTTP/1.1" 200 31
load_balancer-1  | 2025-06-23 21:27:55,990 [DEBUG] [LOAD_BALANCER]
Response from http://substation2:5002: 200 {'status': 'Charging complete'}
load_balancer-1  | 2025-06-23 21:27:55,991 [INFO] [LOAD_BALANCER]
172.23.0.8 - - [23/Jun/2025 21:27:55] "POST /route HTTP/1.1" 200 -
charge_request-1 | 2025-06-23 21:27:55,992 [DEBUG] [CHARGE_SERVICE]
http://load_balancer:5001 "POST /route HTTP/1.1" 200 69
charge_request-1 | 2025-06-23 21:27:55,993 [INFO] [CHARGE_SERVICE]
192.168.65.1 - - [23/Jun/2025 21:27:55] "POST /charge HTTP/1.1" 200 -
substation3     | 2025-06-23 21:27:56,121 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:27:56] "GET /metrics HTTP/1.1" 200 -
substation1     | 2025-06-23 21:27:56,481 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:56] "POST /charge HTTP/1.1" 200 -
load_balancer-1  | 2025-06-23 21:27:56,482 [DEBUG] [LOAD_BALANCER]
http://substation1:5002 "POST /charge HTTP/1.1" 200 31
load_balancer-1  | 2025-06-23 21:27:56,483 [DEBUG] [LOAD_BALANCER]
Response from http://substation1:5002: 200 {'status': 'Charging complete'}
load_balancer-1  | 2025-06-23 21:27:56,484 [INFO] [LOAD_BALANCER]
172.23.0.8 - - [23/Jun/2025 21:27:56] "POST /route HTTP/1.1" 200 -
charge_request-1 | 2025-06-23 21:27:56,485 [DEBUG] [CHARGE_SERVICE]
http://load_balancer:5001 "POST /route HTTP/1.1" 200 69
charge_request-1 | 2025-06-23 21:27:56,486 [INFO] [CHARGE_SERVICE]
192.168.65.1 - - [23/Jun/2025 21:27:56] "POST /charge HTTP/1.1" 200 -
substation3     | 2025-06-23 21:27:56,987 [INFO] [SUBSTATION] 172.23.0.7
- - [23/Jun/2025 21:27:56] "POST /charge HTTP/1.1" 200 -
load_balancer-1  | 2025-06-23 21:27:56,989 [DEBUG] [LOAD_BALANCER]
http://substation3:5002 "POST /charge HTTP/1.1" 200 31
```

```
load_balancer-1    | 2025-06-23 21:27:56,990 [DEBUG] [LOAD_BALANCER]
Response from http://substation3:5002: 200 {'status': 'Charging complete'}
load_balancer-1    | 2025-06-23 21:27:56,990 [INFO] [LOAD_BALANCER]
172.23.0.8 - - [23/Jun/2025 21:27:56] "POST /route HTTP/1.1" 200 -
charge_request-1   | 2025-06-23 21:27:56,991 [DEBUG] [CHARGE_SERVICE]
http://load_balancer:5001 "POST /route HTTP/1.1" 200 69
charge_request-1   | 2025-06-23 21:27:56,992 [INFO] [CHARGE_SERVICE]
192.168.65.1 - - [23/Jun/2025 21:27:56] "POST /charge HTTP/1.1" 200 -
substation1        | 2025-06-23 21:28:00,266 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:00] "GET /metrics HTTP/1.1" 200 -
substation2        | 2025-06-23 21:28:00,284 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:00] "GET /metrics HTTP/1.1" 200 -
substation3        | 2025-06-23 21:28:01,117 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:01] "GET /metrics HTTP/1.1" 200 -
substation1        | 2025-06-23 21:28:05,265 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:05] "GET /metrics HTTP/1.1" 200 -
substation2        | 2025-06-23 21:28:05,285 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:05] "GET /metrics HTTP/1.1" 200 -
substation3        | 2025-06-23 21:28:06,123 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:06] "GET /metrics HTTP/1.1" 200 -
substation1        | 2025-06-23 21:28:10,268 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:10] "GET /metrics HTTP/1.1" 200 -
substation2        | 2025-06-23 21:28:10,283 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:10] "GET /metrics HTTP/1.1" 200 -
substation3        | 2025-06-23 21:28:11,120 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:11] "GET /metrics HTTP/1.1" 200 -
substation1        | 2025-06-23 21:28:15,264 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:15] "GET /metrics HTTP/1.1" 200 -
substation2        | 2025-06-23 21:28:15,286 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:15] "GET /metrics HTTP/1.1" 200 -
substation3        | 2025-06-23 21:28:16,120 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:16] "GET /metrics HTTP/1.1" 200 -
substation1        | 2025-06-23 21:28:20,266 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:20] "GET /metrics HTTP/1.1" 200 -
substation2        | 2025-06-23 21:28:20,286 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:20] "GET /metrics HTTP/1.1" 200 -
substation3        | 2025-06-23 21:28:21,124 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:21] "GET /metrics HTTP/1.1" 200 -
substation1        | 2025-06-23 21:28:25,264 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:25] "GET /metrics HTTP/1.1" 200 -
substation2        | 2025-06-23 21:28:25,284 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:25] "GET /metrics HTTP/1.1" 200 -
substation3        | 2025-06-23 21:28:26,124 [INFO] [SUBSTATION] 172.23.0.2
```

```
- - [23/Jun/2025 21:28:26] "GET /metrics HTTP/1.1" 200 -
substation1     | 2025-06-23 21:28:30,265 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:30] "GET /metrics HTTP/1.1" 200 -
substation2     | 2025-06-23 21:28:30,288 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:30] "GET /metrics HTTP/1.1" 200 -
substation3     | 2025-06-23 21:28:31,120 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:31] "GET /metrics HTTP/1.1" 200 -
substation1     | 2025-06-23 21:28:35,262 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:35] "GET /metrics HTTP/1.1" 200 -
substation2     | 2025-06-23 21:28:35,284 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:35] "GET /metrics HTTP/1.1" 200 -
substation3     | 2025-06-23 21:28:36,120 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:36] "GET /metrics HTTP/1.1" 200 -
substation1     | 2025-06-23 21:28:40,266 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:40] "GET /metrics HTTP/1.1" 200 -
substation2     | 2025-06-23 21:28:40,286 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:40] "GET /metrics HTTP/1.1" 200 -
substation3     | 2025-06-23 21:28:41,122 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:41] "GET /metrics HTTP/1.1" 200 -
substation1     | 2025-06-23 21:28:45,266 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:45] "GET /metrics HTTP/1.1" 200 -
substation2     | 2025-06-23 21:28:45,285 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:45] "GET /metrics HTTP/1.1" 200 -
substation3     | 2025-06-23 21:28:46,123 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:46] "GET /metrics HTTP/1.1" 200 -
substation1     | 2025-06-23 21:28:50,266 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:50] "GET /metrics HTTP/1.1" 200 -
substation2     | 2025-06-23 21:28:50,285 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:50] "GET /metrics HTTP/1.1" 200 -
substation3     | 2025-06-23 21:28:51,123 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:51] "GET /metrics HTTP/1.1" 200 -
substation1     | 2025-06-23 21:28:55,267 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:55] "GET /metrics HTTP/1.1" 200 -
substation2     | 2025-06-23 21:28:55,285 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:55] "GET /metrics HTTP/1.1" 200 -
substation3     | 2025-06-23 21:28:56,124 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:28:56] "GET /metrics HTTP/1.1" 200 -
substation1     | 2025-06-23 21:29:00,266 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:29:00] "GET /metrics HTTP/1.1" 200 -
substation2     | 2025-06-23 21:29:00,284 [INFO] [SUBSTATION] 172.23.0.2
- - [23/Jun/2025 21:29:00] "GET /metrics HTTP/1.1" 200 -
```

2. Load Balancer

- Acts as the intelligent decision-making unit of the grid.
- Periodically polls all substation `/metrics` endpoints to determine real-time loads.
- Routes each EV request to the substation with the **least current load**.
- Ensures fair and dynamic distribution of requests to avoid overloading.

3. Charge Request Service

- The public-facing API (`POST /charge`) that EVs interact with.
- Forwards each incoming request to the load balancer, which then determines the optimal substation.

4. Load Tester

- A Python script to simulate real-world load by firing multiple concurrent charge requests (e.g., 50+ in rapid succession).
- Helps evaluate system performance under "rush hour" conditions.

```
kdas@Krishanus-Mac-mini smart-grid-load-balancer % python3
load_tester/test.py
2025-06-24 02:57:30,273 [INFO] [TEST] Vehicle 0 sending charge request
2025-06-24 02:57:30,776 [INFO] [TEST] Vehicle 1 sending charge request
2025-06-24 02:57:31,282 [INFO] [TEST] Vehicle 2 sending charge request
2025-06-24 02:57:31,787 [INFO] [TEST] Vehicle 3 sending charge request
2025-06-24 02:57:32,290 [INFO] [TEST] Vehicle 4 sending charge request
2025-06-24 02:57:32,318 [INFO] [TEST] Vehicle 0 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:32,793 [INFO] [TEST] Vehicle 5 sending charge request
2025-06-24 02:57:32,808 [INFO] [TEST] Vehicle 1 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:33,298 [INFO] [TEST] Vehicle 6 sending charge request
2025-06-24 02:57:33,323 [INFO] [TEST] Vehicle 2 response: {'status':
'Charging started', 'substation': 'http://substation3:5002'}
2025-06-24 02:57:33,803 [INFO] [TEST] Vehicle 7 sending charge request
```

```
2025-06-24 02:57:33,825 [INFO] [TEST] Vehicle 3 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:34,305 [INFO] [TEST] Vehicle 8 sending charge request
2025-06-24 02:57:34,335 [INFO] [TEST] Vehicle 4 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:34,810 [INFO] [TEST] Vehicle 9 sending charge request
2025-06-24 02:57:34,821 [INFO] [TEST] Vehicle 5 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:35,315 [INFO] [TEST] Vehicle 10 sending charge request
2025-06-24 02:57:35,333 [INFO] [TEST] Vehicle 6 response: {'status':
'Charging started', 'substation': 'http://substation3:5002'}
2025-06-24 02:57:35,820 [INFO] [TEST] Vehicle 11 sending charge request
2025-06-24 02:57:35,835 [INFO] [TEST] Vehicle 7 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:36,325 [INFO] [TEST] Vehicle 12 sending charge request
2025-06-24 02:57:36,348 [INFO] [TEST] Vehicle 8 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:36,828 [INFO] [TEST] Vehicle 13 sending charge request
2025-06-24 02:57:36,839 [INFO] [TEST] Vehicle 9 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:37,332 [INFO] [TEST] Vehicle 14 sending charge request
2025-06-24 02:57:37,352 [INFO] [TEST] Vehicle 10 response: {'status':
'Charging started', 'substation': 'http://substation3:5002'}
2025-06-24 02:57:37,833 [INFO] [TEST] Vehicle 15 sending charge request
2025-06-24 02:57:37,853 [INFO] [TEST] Vehicle 11 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:38,339 [INFO] [TEST] Vehicle 16 sending charge request
2025-06-24 02:57:38,363 [INFO] [TEST] Vehicle 12 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:38,841 [INFO] [TEST] Vehicle 17 sending charge request
2025-06-24 02:57:38,866 [INFO] [TEST] Vehicle 13 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:39,342 [INFO] [TEST] Vehicle 18 sending charge request
2025-06-24 02:57:39,368 [INFO] [TEST] Vehicle 14 response: {'status':
'Charging started', 'substation': 'http://substation3:5002'}
2025-06-24 02:57:39,847 [INFO] [TEST] Vehicle 19 sending charge request
2025-06-24 02:57:39,863 [INFO] [TEST] Vehicle 15 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:40,349 [INFO] [TEST] Vehicle 20 sending charge request
2025-06-24 02:57:40,373 [INFO] [TEST] Vehicle 16 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:40,855 [INFO] [TEST] Vehicle 21 sending charge request
2025-06-24 02:57:40,877 [INFO] [TEST] Vehicle 17 response: {'status':
```

'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:41,355 [INFO] [TEST] Vehicle 22 sending charge request
2025-06-24 02:57:41,383 [INFO] [TEST] Vehicle 18 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:41,861 [INFO] [TEST] Vehicle 23 sending charge request
2025-06-24 02:57:41,882 [INFO] [TEST] Vehicle 19 response: {'status':
'Charging started', 'substation': 'http://substation3:5002'}
2025-06-24 02:57:42,366 [INFO] [TEST] Vehicle 24 sending charge request
2025-06-24 02:57:42,379 [INFO] [TEST] Vehicle 20 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:42,867 [INFO] [TEST] Vehicle 25 sending charge request
2025-06-24 02:57:42,885 [INFO] [TEST] Vehicle 21 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:43,373 [INFO] [TEST] Vehicle 26 sending charge request
2025-06-24 02:57:43,396 [INFO] [TEST] Vehicle 22 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:43,877 [INFO] [TEST] Vehicle 27 sending charge request
2025-06-24 02:57:43,902 [INFO] [TEST] Vehicle 23 response: {'status':
'Charging started', 'substation': 'http://substation3:5002'}
2025-06-24 02:57:44,382 [INFO] [TEST] Vehicle 28 sending charge request
2025-06-24 02:57:44,397 [INFO] [TEST] Vehicle 24 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:44,887 [INFO] [TEST] Vehicle 29 sending charge request
2025-06-24 02:57:44,903 [INFO] [TEST] Vehicle 25 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:45,393 [INFO] [TEST] Vehicle 30 sending charge request
2025-06-24 02:57:45,407 [INFO] [TEST] Vehicle 26 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:45,893 [INFO] [TEST] Vehicle 31 sending charge request
2025-06-24 02:57:45,917 [INFO] [TEST] Vehicle 27 response: {'status':
'Charging started', 'substation': 'http://substation3:5002'}
2025-06-24 02:57:46,398 [INFO] [TEST] Vehicle 32 sending charge request
2025-06-24 02:57:46,417 [INFO] [TEST] Vehicle 28 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:46,903 [INFO] [TEST] Vehicle 33 sending charge request
2025-06-24 02:57:46,928 [INFO] [TEST] Vehicle 29 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:47,407 [INFO] [TEST] Vehicle 34 sending charge request
2025-06-24 02:57:47,423 [INFO] [TEST] Vehicle 30 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:47,912 [INFO] [TEST] Vehicle 35 sending charge request
2025-06-24 02:57:47,928 [INFO] [TEST] Vehicle 31 response: {'status':
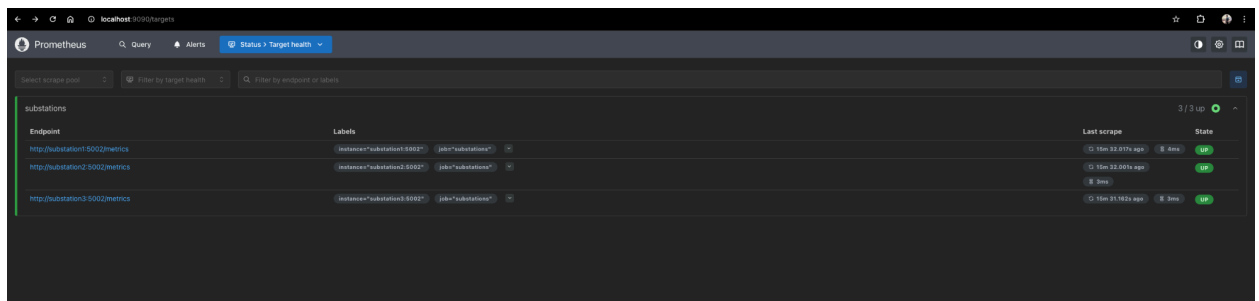'Charging started', 'substation': 'http://substation3:5002'}

2025-06-24 02:57:48,418 [INFO] [TEST] Vehicle 36 sending charge request
2025-06-24 02:57:48,442 [INFO] [TEST] Vehicle 32 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:48,919 [INFO] [TEST] Vehicle 37 sending charge request
2025-06-24 02:57:48,940 [INFO] [TEST] Vehicle 33 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:49,423 [INFO] [TEST] Vehicle 38 sending charge request
2025-06-24 02:57:49,435 [INFO] [TEST] Vehicle 34 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:49,929 [INFO] [TEST] Vehicle 39 sending charge request
2025-06-24 02:57:49,953 [INFO] [TEST] Vehicle 35 response: {'status':
'Charging started', 'substation': 'http://substation3:5002'}
2025-06-24 02:57:50,431 [INFO] [TEST] Vehicle 40 sending charge request
2025-06-24 02:57:50,458 [INFO] [TEST] Vehicle 36 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:50,932 [INFO] [TEST] Vehicle 41 sending charge request
2025-06-24 02:57:50,959 [INFO] [TEST] Vehicle 37 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:51,435 [INFO] [TEST] Vehicle 42 sending charge request
2025-06-24 02:57:51,451 [INFO] [TEST] Vehicle 38 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:51,938 [INFO] [TEST] Vehicle 43 sending charge request
2025-06-24 02:57:51,970 [INFO] [TEST] Vehicle 39 response: {'status':
'Charging started', 'substation': 'http://substation3:5002'}
2025-06-24 02:57:52,444 [INFO] [TEST] Vehicle 44 sending charge request
2025-06-24 02:57:52,469 [INFO] [TEST] Vehicle 40 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:52,945 [INFO] [TEST] Vehicle 45 sending charge request
2025-06-24 02:57:52,971 [INFO] [TEST] Vehicle 41 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:53,451 [INFO] [TEST] Vehicle 46 sending charge request
2025-06-24 02:57:53,474 [INFO] [TEST] Vehicle 42 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:53,954 [INFO] [TEST] Vehicle 47 sending charge request
2025-06-24 02:57:53,976 [INFO] [TEST] Vehicle 43 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:54,456 [INFO] [TEST] Vehicle 48 sending charge request
2025-06-24 02:57:54,477 [INFO] [TEST] Vehicle 44 response: {'status':
'Charging started', 'substation': 'http://substation3:5002'}
2025-06-24 02:57:54,961 [INFO] [TEST] Vehicle 49 sending charge request
2025-06-24 02:57:54,974 [INFO] [TEST] Vehicle 45 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:55,490 [INFO] [TEST] Vehicle 46 response: {'status':

```
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:55,995 [INFO] [TEST] Vehicle 47 response: {'status':
'Charging started', 'substation': 'http://substation2:5002'}
2025-06-24 02:57:56,488 [INFO] [TEST] Vehicle 48 response: {'status':
'Charging started', 'substation': 'http://substation1:5002'}
2025-06-24 02:57:56,995 [INFO] [TEST] Vehicle 49 response:
```

5. Observability Stack

- **Prometheus** scrapes metrics from each substation at a 5-second interval.
- **Grafana** visualizes substation loads using a custom dashboard.
- Each substation appears as a separate time series using the `instance` label
  (`substation1:5002`, etc.).

Prometheus Health Check:

Grafana Live Test Dashboard:

Implementation Highlights

- Fully built in **Python (Flask)** for clean microservice logic.
- **Prometheus metric format** implemented manually for full control.
- Uses `threading.Lock()` to safely track concurrent load in substations.
- Grafana dashboard provides:
  - Real-time view of each substation's load.
  - Easy identification of imbalances or spikes in demand.
- Robust load balancer handles offline substations gracefully (returns 503 if none are available).

Testing and Results

Using the `load_tester`, we simulated 50 EVs requesting charging within a short time window. The system was observed via Grafana during this test, and the following behavior was confirmed:

- The load balancer evenly distributed the requests based on real-time metrics.
- Substations operated independently without any race conditions or crashes.
- The Grafana dashboard clearly showed three distinct time series with dynamic variation in load, confirming correct routing.

Conclusion

The project successfully demonstrates how a distributed, observable smart grid infrastructure can be built using modern tools and practices. The system is:

- **Scalable**: More substations can be added.
- **Observable**: Real-time metrics make system health and behavior transparent.
- **Resilient**: Load balancer adapts to changes in substation availability and load.

The implementation meets all functional and technical requirements laid out in the assignment and reflects a production-style distributed systems design approach.

Video Link

🎬 Dynamic_Load_Balancing_for_a_Smart_Grid.mov